The Geological Society of America
Field Guide 18
2010

Beyond Colorado's Front Range—A new look at Laramide basin subsidence, sedimentation, and deformation in north-central Colorado

James C. Cole
U.S. Geological Survey, MS 980, Box 25046, Denver, Colorado 80225, USA

James H. Trexler Jr.
Patricia H. Cashman
Department of Geological Sciences, MS 172, University of Nevada, Reno, Nevada 89557, USA

Ian M. Miller
Denver Museum of Nature & Science, 2001 Colorado Blvd., Denver, Colorado 80205, USA

Ralph R. Shroba
Michael A. Cosca
Jeremiah B. Workman
U.S. Geological Survey, MS 980, Box 25046, Denver, Colorado 80225, USA

ABSTRACT

This field trip highlights recent research into the Laramide uplift, erosion, and sedimentation on the western side of the northern Colorado Front Range. The Laramide history of the North Park–Middle Park basin (designated the Colorado Headwaters Basin in this paper) is distinctly different from that of the Denver basin on the eastern flank of the range. The Denver basin stratigraphy records the transition from Late Cretaceous marine shale to recessional shoreline sandstones to continental, fluvial, marsh, and coal mires environments, followed by orogenic sediments that span the K-T boundary. Upper Cretaceous and Paleogene strata in the Denver basin consist of two mega-fan complexes that are separated by a 9 million-year interval of erosion/non-deposition between about 63 and 54 Ma.

In contrast, the marine shale unit on the western flank of the Front Range was deeply eroded over most of the area of the Colorado Headwaters Basin (approximately one km removed) prior to any orogenic sediment accumulation. New ^{40}Ar-^{39}Ar ages indicate the oldest sediments on the western flank of the Front Range were as young as about 61 Ma. They comprise the Windy Gap Volcanic Member of the Middle Park Formation, which consists of coarse, immature volcanic conglomerates derived from nearby alkalic-mafic volcanic edifices that were forming at about 65–61 Ma. Clasts of Proterozoic granite, pegmatite, and gneiss (eroded from the uplifted

Cole, J.C., Trexler, Jr., J.H., Cashman, P.H., Miller, I.M., Shroba, R.R., Cosca, M.A., and Workman, J.B., 2010, Beyond Colorado's Front Range—A new look at Laramide basin subsidence, sedimentation, and deformation in north-central Colorado, *in* Morgan, L.A., and Quane, S.L., eds., Through the Generations: Geologic and Anthropogenic Field Excursions in the Rocky Mountains from Modern to Ancient: Geological Society of America Field Guide 18, p. 55–76, doi: 10.1130/2010.0018(03). For permission to copy, contact editing@geosociety.org.

core of the Front Range) seem to arrive in the Colorado Headwaters Basin at different times in different places, but they become dominant in arkosic sandstones and conglomerates about one km above the base of the Colorado Headwaters Basin section. Paleocurrent trends suggest the southern end of the Colorado Headwaters Basin was structurally closed because all fluvial deposits show a northward component of transport. Lacustrine depositional environments are indicated by various sedimentological features in several sections within the >3 km of sediment preserved in the Colorado Headwaters Basin, suggesting this basin may have remained closed throughout the Paleocene and early Eocene.

The field trip also addresses middle Eocene(?) folding of the late Laramide basin-fill strata, related to steep reverse faults that offset the Proterozoic crystalline basement.

Late Oligocene magmatic activity is indicated by dikes, plugs, and eruptive volcanic rocks in the Rabbit Ears Range and the Never Summer Mountains that span and flank the Colorado Headwaters Basin. These intrusions and eruptions were accompanied by extensional faulting along predominantly northwesterly trends. Erosion accompanied the late Oligocene igneous activity and faulting, leading to deposition of boulder conglomerates and sandstones of the North Park Formation and high-level conglomerates across the landscape that preserve evidence of a paleo-drainage network that drained the volcanic landscape.

INTRODUCTION

The major elements of Colorado's landscapes were established during the protracted Laramide orogeny in response to contractional deformation that affected most of western North America (Tweto, 1975; Dickinson and Snyder, 1978). Prolonged, slow, continental subsidence during most of Late Cretaceous time allowed thick deposits of marine shale to accumulate in the Interior Seaway that stretched from the Gulf of Mexico to the Canadian Arctic. The western margin of the Seaway was deformed by thin-skinned thrusting within the Phanerozoic sedimentary sequence in the Overthrust Belt of western Wyoming and northeastern Utah, beginning in mid-Cretaceous time. The Laramide orogeny, although driven by the same major tectonic forces that produced the Overthrust Belt, was a distinctly different event in structural style, space, and time. Laramide deformation produced broad anticlinal uplifts and broad synclinal swales in the Precambrian crystalline basement within an arcuate swath across southern Montana, Wyoming, Colorado, and northern New Mexico, referred to as the Laramide foreland (Dickinson and Snyder, 1978). The buckling, uplift, and subsidence of the foreland basement seems to have begun nearly synchronously in a relatively brief span during latest Cretaceous time across the foreland and persisted into early or middle Eocene time in various Laramide basins (Dickinson et al., 1988).

TRIP OVERVIEW

The field trip begins at the Colorado Convention Center in downtown Denver and passes westward on Sixth Avenue/Interstate 70 across the Front Range uplift (Fig. 1). At Empire, we leave I-70 and continue westward on U.S. 40 over the Continental Divide at Berthoud Pass and then northward into Winter Park, Fraser, and Granby in the Colorado River drainage. The first stops are west of Granby along the Colorado River; after retracing steps a few miles, the trip continues northward on CO 125 up the Willow Creek drainage, over Willow Creek Pass, and on to Walden, Colorado, for the end of the first day. The second day includes several stops in the North Park basin around Walden to examine the Coalmont Formation, and then a traverse out the southwestern corner of the basin over Muddy Pass. Here, the trip rejoins U.S. 40 and descends southeastward along the Muddy Creek drainage into Kremmling, follows the Colorado River eastward upstream through Hot Sulphur Springs, and then back through Granby to Fraser, and finally returns to Denver.

This field trip explores the timing and geometry of Laramide uplift of the Colorado Front Range west of Denver. The record of these events is contained in the sediments that accumulated in the synclinal basins on the flanks of the Front Range uplift. Synorogenic sediments contained in the Denver Basin east of the Front Range have been studied in detail over the past few decades (Soister, 1978; Raynolds, 2002; Raynolds et al., 2007) and can be interpreted as a chronology of uplift, erosion, drainage evolution, and sedimentation east of the Front Range. The main focus of this field trip will be to examine the sediments that accumulated west of the Front Range in the structural basin that encompasses Granby, Hot Sulphur Springs, and Walden, Colorado (Fig. 1).

Colorado Headwaters Basin

This Laramide-age basin underlies the physiographic lowlands named North Park and Middle Park by early settlers in recognition of the broad expanses of relatively flat, grass-covered terraces and pediments alongside the major through-flowing rivers. The structural basin (referred to in prior literature as the "North Park–Middle Park basin"; e.g., Tweto, 1957, 1975) is an

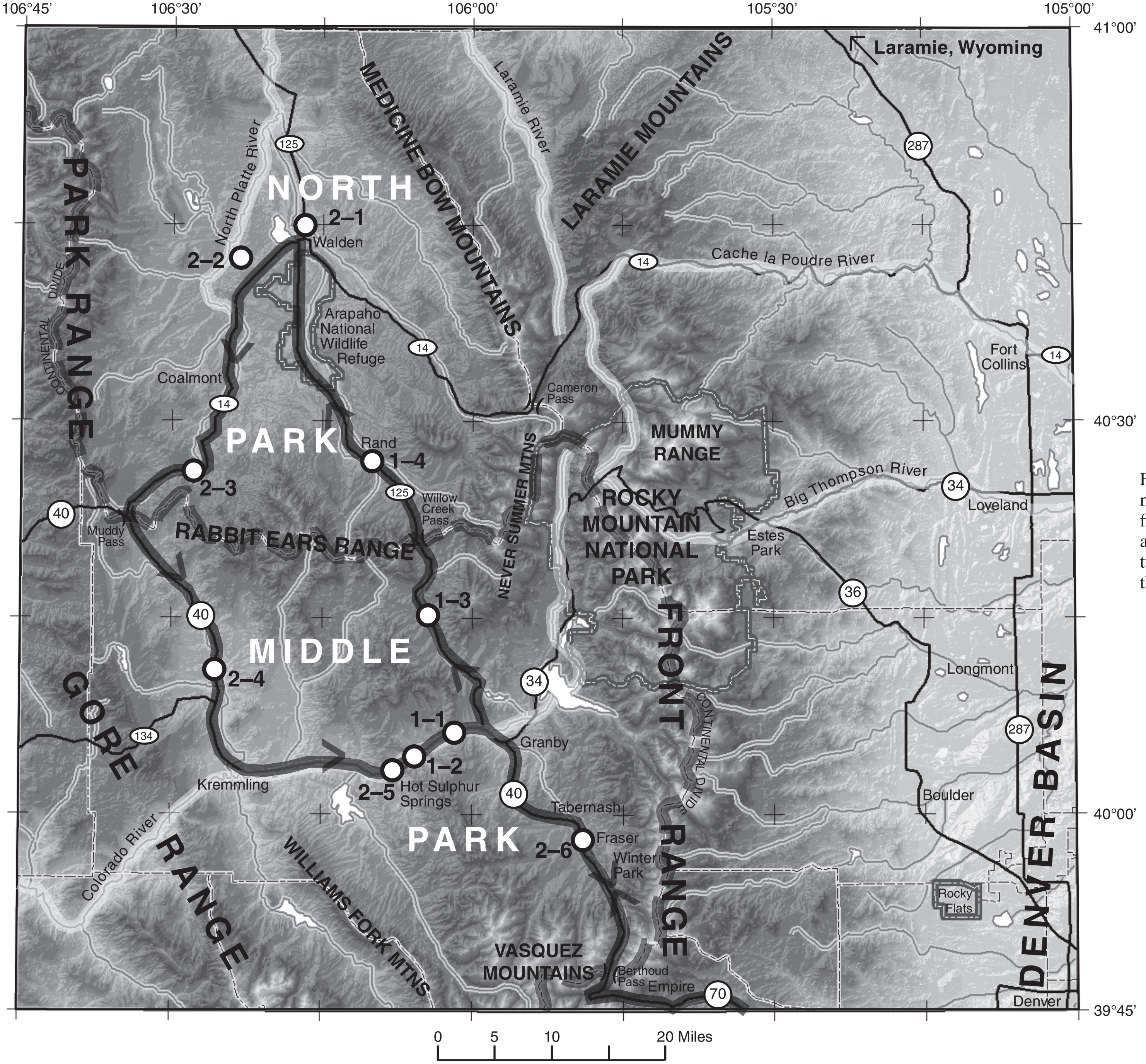

Figure 1. Shaded-relief map of north-central Colorado showing field trip route, stop locations, and principal geographic features. Major rivers that head in this area are highlighted.

older feature underlying the modern landscape and only generally coincides with the expansive park lands in North Park. We will refer to the structural basin as the Colorado Headwaters Basin in this guide because the area contains the sources of the Colorado River and the North Platte River and is near the headwaters of the Cache la Poudre River and the Big Thompson River in western Rocky Mountain National Park and the Laramie River (Fig. 1).

The Colorado Headwaters Basin today is physiographically divided by the Continental Divide that passes east-west along the crest of the Rabbit Ears Range (coinciding with the Jackson County–Grand County boundary). As described below, the Rabbit Ears Range is higher in elevation due to the presence of numerous resistant dikes and stocks of late Oligocene age that postdate the Paleocene and Eocene sedimentary rocks that filled the structural basin during late Laramide time.

Previous Work

Sedimentary basins on the west side of the Front Range were investigated by Beekly (1915) for coal resources. He defined the Coalmont Formation in North Park and elaborated on earlier work by the Hayden Survey of 1869 on the sedimentary sequence of the broadly contemporaneous Middle Park Formation south of the Continental Divide. Sporadic oil exploration was conducted in the North Park part of the Colorado Headwaters Basin in the 1920s–1950s, and short summaries of the stratigraphy and structure were compiled in the 1957 Rocky Mountain Association of Geologists' Fieldtrip Guidebook. The volume included a useful and comprehensive summary of the geologic and tectonic setting of the region by Ogden Tweto that remains both pertinent and relevant today (Tweto, 1957).

Systematic reconnaissance geologic mapping was conducted by the U.S. Geological Survey in the late 1960s and early 1970s in the North Park basin, also in connection with coal resource investigations (Hail, 1965; Kinney, 1970). Bill Hail produced two USGS Bulletins describing the geology of northwestern and southwestern North Park in connection with that mapping that are the best existing summaries of the area (Hail, 1965, 1968). Those bulletins also summarize considerable biostratigraphic work (pollen) done by Estella Leopold that demonstrated the Coalmont Formation is Paleocene–early Eocene in age (see also Hail and Leopold, 1960). Eastern North Park was mapped by Kinney (1970).

At about the same time, Glen Izett began mapping the Hot Sulphur Springs quadrangle south of the Rabbit Ears Range. The USGS Professional Paper documenting his investigations (Izett, 1968) is the most comprehensive summary of the geologic setting and stratigraphy of the Middle Park Formation to date. Izett summarized paleobotanical information (leaves and pollen, largely determined by R. Tschudy, USGS) that demonstrated most of the Middle Park Formation is Paleocene in age. One pollen sample and one fossil leaf locality near the base of the unit suggested a possible Late Cretaceous age. On these grounds, Izett et al. (1963) assigned an age of Late Cretaceous(?) and Paleocene to the Middle Park Formation. They also appeared to have been influenced by the lithologic similarities of the basal Middle Park Formation (Windy Gap Volcanic Member) to the Denver Formation of the Denver Basin, which was known to span the interval of the Cretaceous-Tertiary (K-T) boundary (Scott, 1972; Soister, 1978). We present evidence in this guide that the Middle Park Formation was deposited at a different time than the lithologically similar deposits of the Denver Basin.

Izett and Barclay (1973) continued work in the area and produced the geologic map of the Kremmling 15-minute quadrangle. Izett worked with various vertebrate paleontologists on the faunal remains in the type area of the Oligocene and Miocene Troublesome Formation, and with several geochronologists to obtain numerical ages for numerous volcanic-ash beds in the sequence. Izett's interests in the paleontology, stratigraphy, and sedimentology of the Troublesome and Browns Park Formations in the region are documented in the Geological Society of America Special Paper 144 on the Laramide Orogeny (Izett, 1975).

Detailed maps along the margins of the Colorado Headwaters Basin were completed by Steven (1960), Izett (1974), Taylor (1975), Snyder (1980), O'Neill (1981), Schroeder (1995), Shroba et al. (2010), and Cole et al. (2010). Geology in the northeastern part of the Colorado Headwaters Basin is summarized in the Estes Park 30′ × 60′ quadrangle (Cole and Braddock, 2009), and in the Fort Collins 30′ × 60′ quadrangle (Workman and others, in preparation). Regional compilations of surficial geology in the area were produced by Madole (1991a, 1991b).

Renewed interest in coal resources of the Rocky Mountain region led to a USGS geologic assessment of coal potential (Madden, 1977) that involved an extensive drilling program surrounding the historic coal-mining district at Coalmont, Colorado. Sedimentologic studies of the Coalmont Formation conducted by Flores (1990) documented the presence of lake-basin delta complexes in the formation. A revised stratigraphic model for the Coalmont was described by Roberts and Rossi (1999), based in part on work by Hendricks (1978) and Stands (1992).

DENVER BASIN STUDIES

The field trip begins in the Denver Basin on the eastern side of the Front Range uplift, so it is relevant to summarize the geology of the synorogenic deposits related to the Laramide orogeny in this area. The Laramide synorogenic sediments have been the subject of considerable study over the last few decades because they comprise the aquifers that provide groundwater for growing residential population in the south suburban areas of the greater Denver metropolitan region. These investigations have been led by the Denver Museum of Nature & Science, Colorado Geological Survey, Colorado Office of the State Engineer, several water districts, and the USGS. The following summary is excerpted from a report by Raynolds et al. (2007) and earlier summaries (Tweto, 1975; Raynolds, 2002).

During Late Cretaceous time, black, carbonaceous, marine shales of the Pierre Shale accumulated within the vast Interior Seaway (Fig. 2). At ca. 67.7 Ma, sea level declined and shoreline sands of the regressional Fox Hills Sandstone were deposited along the west margin of the receding sea. Continental, lagoonal, and swamp deposits of the Laramie Formation interfingered with the Fox Hills and prograded eastward over the shoreline sandstones. At ca. 66 Ma, synorogenic deposits (Arapahoe Formation and Denver Formation; later designated the D1 sequence) began filling the subsiding Denver Basin in response to uplift and erosion of the Front Range basement block. Lower beds of the Denver Formation contain abundant clasts of alkalic-mafic volcanic rock (trachybasalt, shoshonite, and trachyandesite) that were presumably eroded from contemporaneous volcanic centers within the Front Range to the west. Volcanoes may have formed above the intrusive complexes of the Apex stock (68 Ma), Caribou stock (68 Ma), Audubon-Albion stock (72–68 Ma), and contemporaneous igneous systems of the region (Cole and Braddock, 2009). Younger beds contain increasing proportions of arkosic material derived from unroofing and stripping of the Proterozoic crystalline basement composed of granites and gneisses (Wilson, 2002). Fluvial, synorogenic deposits continued to build a large alluvial fan complex on the eastern side of the Front Range over the Denver Basin through the K-T boundary interval until ca. 63.9 Ma (Obradovich, 2002). Denver Basin sedimentation either ceased at this time, or later sediments were removed by erosion, and an

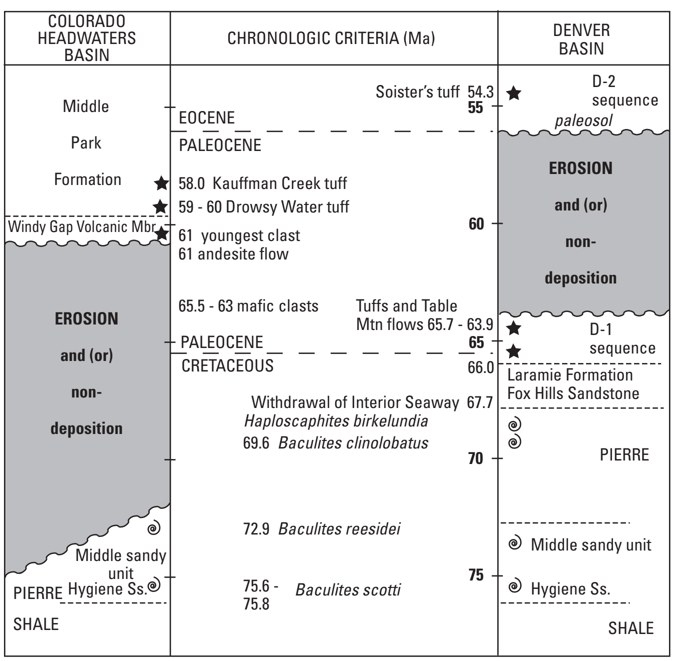

Figure 2. Time-stratigraphic diagram showing contrasting records of sedimentation and erosion in the Colorado Headwaters Basin and the Denver Basin. Age and fossil information are compiled from Obradovich and Cobban (1975), Obradovich (2002), Raynolds (2002), and this paper. Solid stars represent approximate position of volcanic samples; swirl symbol shows approximate position of marine ammonoid fossils (names in italics). D-1 and D-2 sequences are informal stratigraphic units of Raynolds (2002). Named tuffs are informal units designated for specific exposure localities.

extensive soil was formed. Additional synorogenic sediments (designated the D2 sequence) were deposited above the paleosol, beginning in Eocene time, sometime shortly before 54 Ma.

DAY ONE

Things to See on the Way

Depart the Colorado Convention Center in downtown Denver and cross the north-flowing South Platte River and Interstate 25 while traveling westward on Sixth Avenue through the western suburbs of the metropolitan area. On the north (right-hand side) approaching the foothills, note the lava-capped mesas of North and South Table Mountains near Golden, Colorado. These mafic-alkalic lavas (shoshonite) were erupted at ca. 63–64 Ma from a nearby source to the north (Obradovich, 2002). The lower slopes of South Table Mountain show gray and greenish gray siltstones and sandstones of the coal-bearing, fluvial Denver Formation. The K-T boundary has been documented in these beds with pollen, leaves, and vertebrate remains (Kauffman et al., 1990).

Exit Sixth Avenue and merge with I-70 westward toward Grand Junction. Near the mountain front, the highway passes through a spectacular roadcut that exposes the Lower Cretaceous Dakota Sandstone and multicolored fluvial sandstones of the Upper Jurassic Morrison Formation, all dipping ~60° eastward. Both units are renowned for dinosaur fossils and trackways (fossil footprints) that are well displayed in local parks and interpretive sites. Several miles south of I-70 at the foot of the Front Range uplift, dark maroon and purple sandstones of the Middle Pennsylvanian–Lower Permian Fountain Formation are exposed in a natural amphitheater that forms a concert venue at Red Rocks Park. The Fountain Formation is not present where I-70 crosses into the Proterozoic metamorphic rocks of the Front Range because it is cut out by the west-dipping Golden (reverse) fault for many miles to the north.

Continuing westward, I-70 climbs through the crystalline basement rocks of the Front Range. Large roadcuts show complex metamorphic gneisses with intricate compositional banding of hornblende-feldspar gneisses, quartz-feldspar leucocratic gneisses, and biotite-sillimanite gneisses, locally cut by irregular discordant bodies of white and pink pegmatite. These metamorphic rocks were derived from mafic-felsic volcanic rocks and greywacke-type metasediments that accumulated in northern Colorado after ca. 1800 Ma and were strongly deformed and metamorphosed at ca. 1720–1710 Ma (Cole and Braddock, 2009).

At Idaho Springs, evidence of past mining activity is conspicuous by small and large deposits of mine tailings that display characteristic yellow, orange, and brown colorations related to alteration and oxidation of sulfide minerals. Idaho Springs was one of the major centers of hard-rock mining in Colorado between the late 1800s and the early 1900s. Most of the deposits are hydrothermal vein deposits consisting of quartz, metallic sulfides, and gold or silver ores localized around early Tertiary intrusive bodies and fracture zones in the Proterozoic basement rocks.

Approximately 43 mi west of downtown Denver, depart I-70 at exit 232 for Highway U.S. 40 at Empire. After passing through the small mountain town of Empire (another mining center of the late 1800s), watch for homogeneous, medium-gray outcrops on the north (right-hand side) of the highway. These outcrops and roadcuts expose the early Tertiary Empire stock, an amphibole-pyroxene-bearing monzonite pluton that is roughly circular in plan and ~1.5 mi in diameter (Braddock, 1968). The Empire stock (ca. 58 Ma; E. DeWitt, USGS, 2009, personal commun.) is representative of the alkalic-mafic igneous suite of magmas intruded during the onset of the Laramide orogeny.

Over the Continental Divide at Berthoud Pass

Highway U.S. 40 continues westward for a few more miles along Clear Creek and then turns northward through several switchbacks to attain the summit of Berthoud Pass at 11,315 ft above sea level. Many surrounding peaks exceed 13,000 ft. The local bedrock here is mostly gray and yellowish-gray medium-grained biotite granite of the Silver Plume batholith that intruded the Proterozoic metamorphic basement at ca. 1400 Ma. In Late Cretaceous time just prior to onset of the Laramide orogeny, these same basement rocks must have been at least 12,000 ft below sea level (based on cumulative thickness of Phanerozoic sediments stripped off the basement) when the shoreline Fox Hills Sandstone was deposited (Fig. 2). The total uplift of at least 25,000 ft was not all accomplished during the Laramide orogeny. Estimates vary, but much of the modern high altitude of the Southern Rocky Mountains seems to result from late Miocene–Pliocene uplift (Eaton, 2008).

Looking southward from the switchbacks below (south of) Berthoud Pass, the conspicuous hydrothermal alteration at Red Mountain is apparent just south of the glaciated valley of Clear Creek. Red Mountain is host to the Henderson porphyry molybdenum deposit that formed between ca. 29 Ma and 26 Ma (Geissman et al., 1992) around a high-silica granite intrusion. Henderson is one of three world-class molybdenum deposits in Colorado.

Continue north on U.S. 40 past the Winter Park ski area and through the town of Winter Park. In the center of the commercial district at the Rendezvous Way intersection (signal light; community park and children's play area on right), look right (east) at the gray-brown, block-covered slope on the far side of the Fraser River valley bottom. This material is rubble weathered from outcrop of quartz-bearing rhyolite ash-flow tuff that erupted at ca. 27.3 Ma (Knox, 2005). The most likely source (based on age, chemistry, and isotopes; Stein and Crock, 1990) is the high-silica granite at Red Mountain, presently located on the other side of the Continental Divide (Berthoud Pass). Implications of these relations for paleotopography and drainage evolution are discussed below (Stop 2-6).

Continue north and west on U.S. 40 through Fraser and Tabernash. Approximately 4 miles west of Tabernash, U.S. 40 traverses a gentle divide between the Fraser and Granby basins (near the turnoff to Snow Mountain Ranch, YMCA of the Rockies). On the north (right), notice fractured pale yellow-brown outcrops of the Lower Cretaceous Dakota Sandstone that are faulted against an anticlinal block of Proterozoic granodiorite to the west (downhill). Nearby to the north, this Mesozoic section is intruded by thick sills of mafic-alkalic latite that contain conspicuous black phenocrysts of augite pyroxene; Schroeder (1995) determined an intrusion age of 66 ± 4 Ma by fission-track methods on zircon. Similar rock is present as clasts in the basal member of the Paleocene Middle Park Formation (Stop 1-1).

Granby Basin

Continue north on U.S. 40 into the broad Granby basin that is mostly underlain by upper Oligocene and upper Miocene Troublesome Formation (Cole and Braddock, 2009). Mountains to the east are almost entirely composed of Proterozoic crystalline rock in Rocky Mountain National Park (Braddock and Cole, 1990). The highway crosses the Fraser River and turns west through the town of Granby. The town is situated on remnants of several fluvial terraces that formed during aggradational episodes related to discharge fluctuations on both the Fraser and Colorado Rivers in response to Pleistocene glacial-interglacial oscillations (Cole and Braddock, 2009). About 2 mi west of Granby, U.S. 40 crosses the Colorado River and passes the junction with CO 125 (road to Willow Creek Pass and Walden). About 0.5 mi west of the junction, park on the north (right) side of U.S. 40 before the steep, dark cliffs at Windy Gap.

STOP 1-1: WINDY GAP

This stop is located at the unconformable margin of the Colorado Headwaters Basin (Fig. 3) where overlying deposits record the history of sedimentation related to Laramide uplift of the Front Range basement. The dark cliffs to the west expose basal strata of the Windy Gap Volcanic Member of the Middle Park Formation (Izett, 1968). They were deposited unconformably on the middle sandy part of the thick marine sequence that makes up the Upper Cretaceous Pierre Shale across most of northeastern Colorado (Fig. 2). Roadcuts located just east of the unconformity expose marine sandstones equivalent to the Hygiene Sandstone Member of the Denver Basin that were deposited in the Late Cretaceous Interior Seaway at ca. 75.8 Ma (*Baculites scotti* zone; Cobban et al., 2006). The youngest clasts in volcanic conglomerates of the overlying Windy Gap Volcanic Member (described below) were erupted from nearby volcanoes at ca. 61 Ma. Thus, the gap in the sedimentary section here is at least 15 million years. Regional comparisons indicate that ~5000 ft of the upper Pierre Shale was removed prior to Windy Gap deposition, along with any Fox Hills–Laramie Formation equivalents that might have been deposited in this area during withdrawal of the Interior Seaway.

Sedimentology of the Windy Gap Volcanic Member

The base of the Windy Gap section here at its type locality is a very poorly sorted polymict, matrix-supported conglomerate

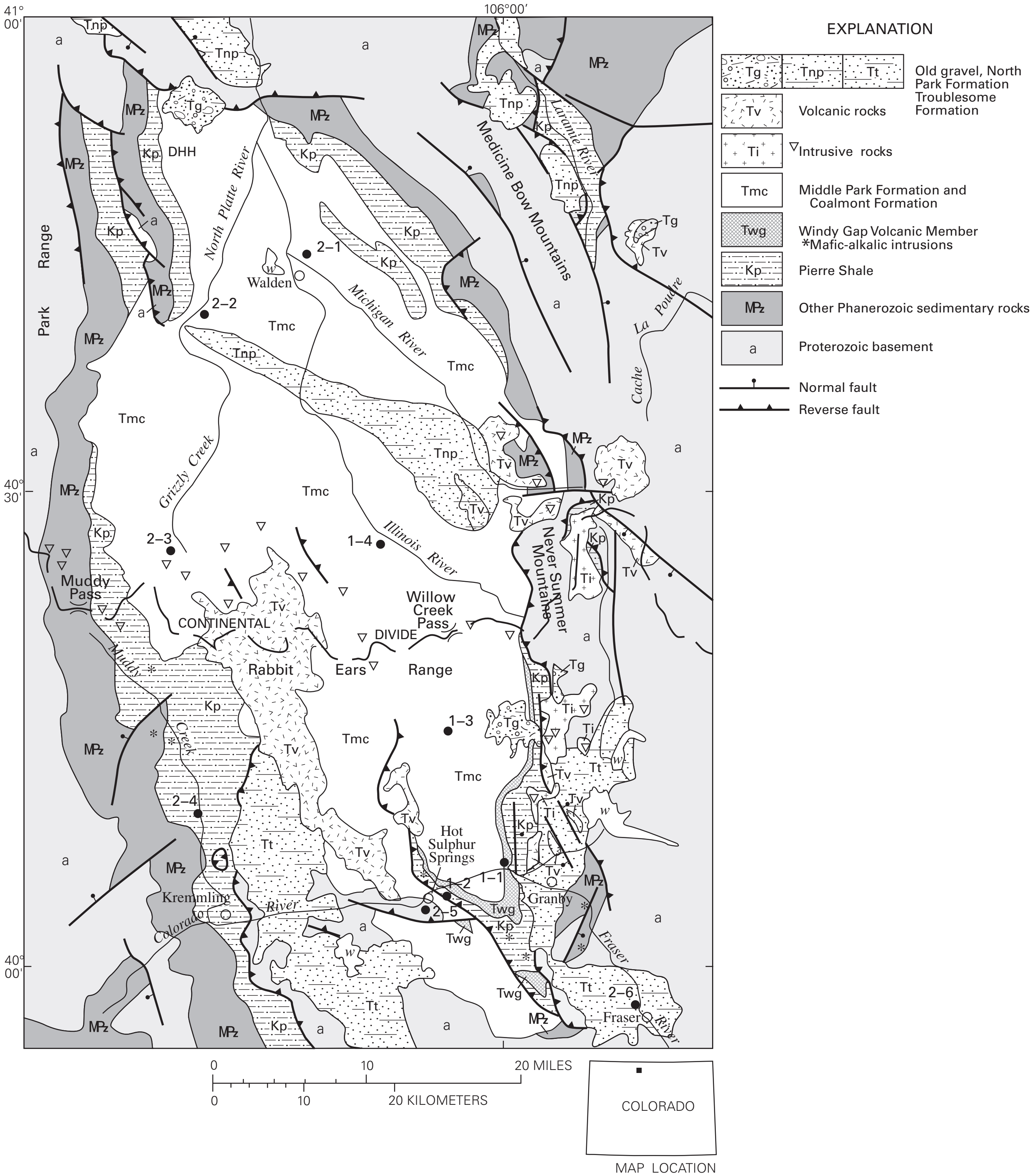

Figure 3. Simplified geologic sketch map of the Colorado Headwaters Basin area (adapted from Tweto, 1979). Late Cretaceous and early Paleocene intrusive bodies of mafic-alkalic composition (indicated by star symbol) may have been connected to volcanoes that were sources of clasts in the Windy Gap Volcanic Member. Late Oligocene intrusive bodies (indicated by triangle symbol) may have been connected to volcanoes across the Rabbit Ears Range and Never Summer Mountains. DHH—Dead Horse Hill.

with a matrix of angular volcanic sand. The clasts are 10–20 cm, round to subangular, and unoriented; they include abundant volcanic debris, along with granite, fine-grained laminated arenite, and shale (the latter two probably from the underlying Pierre). The largest clasts are volcanic; some of the smaller clasts are rounded, recycled fluvial pebbles including Proterozoic granitic rocks. Although angular granite clasts dominate some debris flow units near the base of the section, granite is much less common upward. The lowest part of the Windy Gap Volcanic Member is interpreted as various density-modified flow deposits reworking a variety of surface material into the Colorado Headwaters Basin.

Upward, the section contains progressively coarser debris-flow conglomerate units, composed almost exclusively of volcanic rocks. Although volcanic clasts predominate, small granitic clasts are present at many horizons, and sparse limestone and shale clasts are also present. No radial fractures were observed, even in the largest volcanic clasts. A 4-cm-thick weathering rind on a 25-cm clast records extensive weathering at the surface and not much transport before this clast was incorporated into the conglomerate. Individual debris-flow beds are as much as 3–5 m thick and include clasts as much as 2 m long; some intervals exhibit inverse grading. The debris flow conglomerates are matrix-supported but clast-rich, and occur as amalgamated channel deposits. One such channel has 10 m of relief on its base. Paleocurrents, based on the orientation of a channel wall, flowed toward the west. The view from across the river (south) shows the channel-fill nature of the beds; they thin laterally and have flat tops.

The westernmost resistant ledges in this roadcut represent the top of the Windy Gap Volcanic Member. The rocks are muddy, coarse-grained sandstones with floating angular grit and pebbles like those lower in the section, except that they lack intervening conglomerates. The fine-grained beds are laminated coarse to fine and display ripples, rip-ups, scours, and local mudcracks. Muddy graded beds record rapid subaqueous deposition. Mudcracks on laminated fine-grained horizons indicate shallow-water deposition followed by desiccation. Paleocurrents, determined from parting lineations, trough cross-beds, and oriented plant fragments on bedding surfaces, flowed west and northwest. We have not seen any granite or other exotic clasts in this part of the section. A crystal-rich lithic tuff high in the member was sampled for isotopic dating (see below). This part of the section is interpreted as low-energy fluvial, deltaic, and shallow lacustrine.

It is significant that the oldest rocks of the Windy Gap are reworked surface material, not primary volcaniclastic deposits. Although volcanic debris was the major contributor to the sedimentary material, the section includes other sediment that was reworked into this environment, some with inherited sedimentary features. The dominant sedimentary process in this section is subaqueous debris flow and density-modified flow. This section was not deposited on the subaerial slope of a volcanic edifice, but rather records deposition into a lake. Because these flows "froze" in the position we now see them, we infer that depositional dip angle was low.

Clast Sources and Age Constraints

Clasts in the Windy Gap Volcanic Member here were derived chiefly from mafic volcanic rocks, including alkalic basalts and andesites. Rocks with conspicuous, black augite phenocrysts are notable, as well as several other porphyries that contain variable proportions of augite and plagioclase phenocrysts. Hornblende porphyries are present but less common than the pyroxene-bearing rocks. The augite-phenocryst rocks are texturally and mineralogically similar to dikes and small plugs that were intruded into Cretaceous rocks nearby in the Granby valley (Schroeder, 1995). Fine-grained, phenocryst-poor andesite-basalt lava flows are locally present within the Windy Gap (Tweto, 1957) and similar rock makes up a moderate portion of clasts in the Windy Gap volcanic conglomerates. We recently dated two whole rock samples of similar rock (Pole Creek locality, ~5 mi south of here; Taylor, 1975) by $^{40}Ar/^{39}Ar$ methods, with resulting ages of 56 and 60 Ma. Angular clasts of granite, pegmatite, and biotite gneiss are rare but indicate unroofing of Proterozoic basement somewhere in the source area. Clasts of Pierre Shale derived from the immediate substrate have been identified in lowermost beds of the Windy Gap in a few places (Izett, 1968).

Two samples of amphibole-bearing clasts within a finer-grained, amphibole-bearing volcanic matrix were collected from this outcrop for $^{40}Ar/^{39}Ar$ geochronology. For each sample, CO_2 laser incremental heating $^{40}Ar/^{39}Ar$ experiments were made on single amphibole grains separated from both the individual clasts and the whole-rock matrix. Amphiboles from one sample (9JC127-2) yield statistically indistinguishable $^{40}Ar/^{39}Ar$ plateau ages (2σ errors) of 65.5 ± 0.7 Ma (matrix) and 64.3 ± 0.7 Ma (clast). A second sample (9JC127-1) yielded two amphibole grains from one clast that produced nearly identical $^{40}Ar/^{39}Ar$ plateau ages of 60.5 ± 0.4 Ma and 60.4 ± 0.5 Ma. The disparate $^{40}Ar/^{39}Ar$ ages from these two rock samples are consistent with multiple source inputs to this volcanic breccia and suggest evolution of a volcanic field over several million years duration. The younger amphibole ages place maximum age limits on this member of the Middle Park Formation and indicate sedimentation did not begin until early Paleocene time (after ca. 60.5 Ma; Fig. 2).

The basal unconformity of the Windy Gap Volcanic Member is inclined steeply westward here due to post–Middle Park Formation folding and faulting. These west-dipping beds form the eastern limb of the broad, north-plunging Breccia Spoon syncline (Fig. 4), so-named because the outcrop ridge marking the resistant Windy Gap Volcanic Member (with coarse, angular conglomerate) resembles the form of a spoon (Tweto, 1957). The core of the syncline is quite broad and flat even though the margins are steeply tilted (more like a coal shovel than a spoon). This geometry suggests the fold form reflects steep reverse faulting along the margins rather than buckling (Cole et al., 2010).

Continue westward on U.S. 40 across the Breccia Spoon syncline. The highway crosses the western limb of the syncline where it also crosses the Colorado River and the railroad tracks. Banded, brown cliffs on the north (right) show irregular bedding and coarse

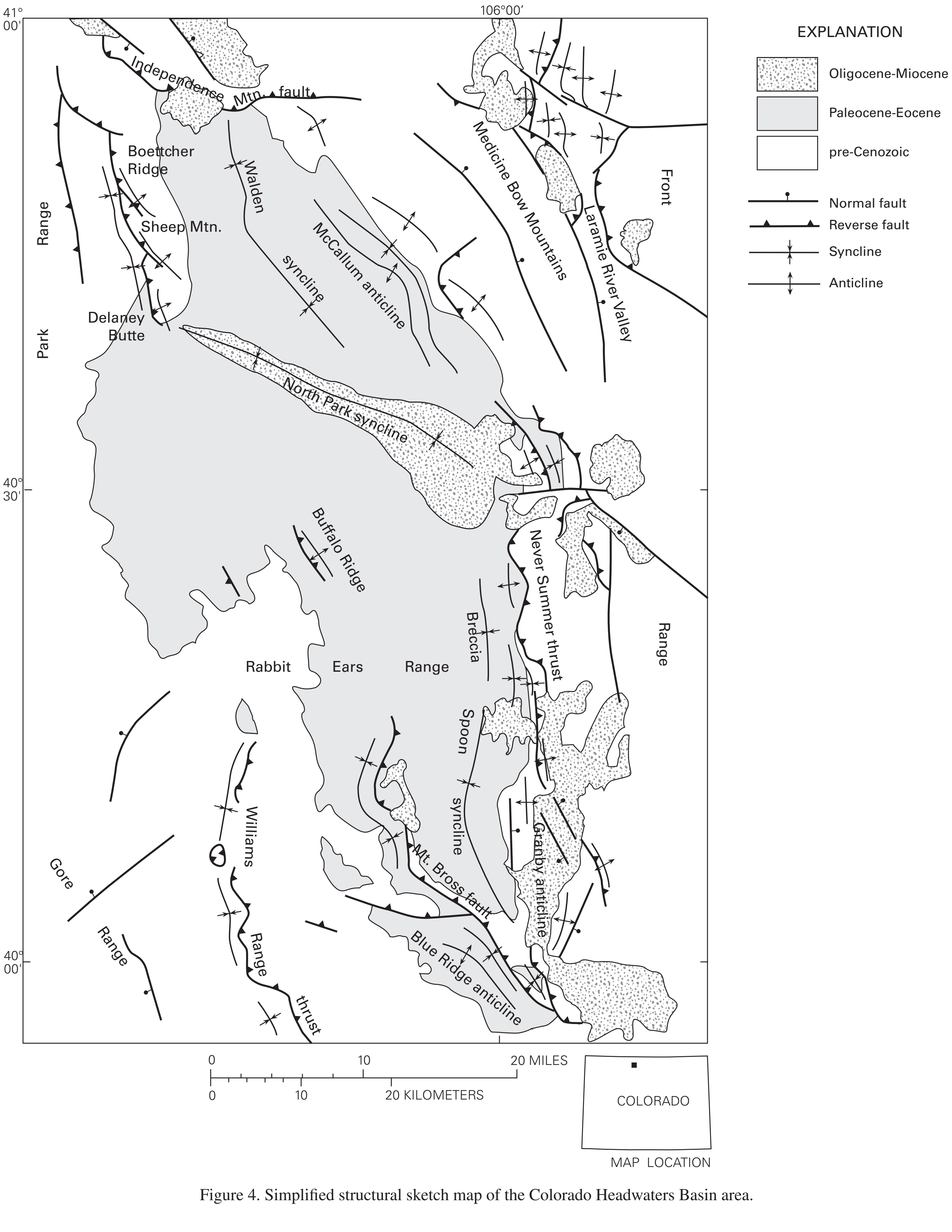

Figure 4. Simplified structural sketch map of the Colorado Headwaters Basin area.

conglomerates within the Windy Gap Volcanic Member. Continue about one mile west to the outskirts of Hot Sulphur Springs. At First Street, turn left (south) and immediately left again (east) on Byers Avenue (CR 55) in the direction of Cottonwood Pass. About 0.5 mi east of town, turn north (left) and enter the Hot Sulphur Springs Cemetery; drive to the top of the hill and park.

STOP 1-2: HOT SULPHUR SPRINGS OVERLOOK

The vantage from this spot presents a look into the sedimentary architecture of the Paleocene deposits of the Colorado Headwaters Basin. The low terrain in the foreground is underlain by the Upper Cretaceous Pierre Shale, and the gently inclined, low ridge of yellow-brown sandstone is the Hygiene Sandstone Member (as seen on the east side of the Breccia Spoon syncline). This relation (commonly observed beneath the Paleocene beds of the Colorado Headwaters Basin) indicates that the Late Cretaceous stripping of the upper part of the Pierre Shale was not preceded by tilting over large areas. By inference, the unconformity above the underlying crystalline basement was also not tilted while ~5000 ft of shale was removed.

Middle Park Formation Sedimentary Architecture

We measured a composite section of ~1000 m of the Middle Park Formation in the west limb of the syncline. The Windy Gap Member is almost 200 m thick. The top of the Windy Gap is marked by the abrupt appearance of granite clasts and the highest and last very coarse volcaniclastic debris flow deposits; granite is the dominant rock type in the first conglomerate overlying the Windy Gap and continues to dominate the section upward.

The Windy Gap Volcanic Member on the west flank of the Breccia Spoon syncline is 180 m thick, and characterized by channelized, matrix-supported, volcaniclastic conglomerate interbedded with coarse-grained, bedded volcanic arenite. Some of the finer grained horizons have volcanic pebbles (≤1–2 cm) at the tops of inversely graded beds, and locally contain boulders floating in a matrix of muddy sandstone. Plant debris, in the form of silicified logs and molds of logs, is noted in some of the conglomerate beds. Unlike the Windy Gap Volcanic Member on the east flank of the syncline, these rocks show no evidence of subaerial exposure. Volcanic clasts at the base of the section are plagioclase porphyry or plagioclase-augite porphyry. The distinctive augite porphyry clasts that characterize the base of the east limb (see Stop 1-1) first appear abruptly at 122 m above the base of the section on the west limb. Clasts of augite porphyry increase in size and frequency upward, dominating the top 60 m of the section. A locally laminated sequence of fining-upward sandy beds in this part of the section contains more than 20% augite grains.

The internal structure of the Windy Gap Volcanic Member is apparent from this distance: The volcaniclastic deposits fill channels in the paleotopography. Tilting observed in some layers is absent in the overlying layers. This relation is noted at more than one stratigraphic horizon, suggesting rapid deposition and ongoing, gravity-driven deformation throughout the formation of the unit. Viewed from the west, the basal channel deposits appear to be shingled in a pattern indicating northward progradation of a lacustrine delta complex.

The Middle Park Formation above the Windy Gap Volcanic Member comprises interbedded conglomerate and arkosic sandstone. Conglomerate forms resistant outcrops and locally accounts for ~10% of the section. Clasts are dominantly granite but volcanic clasts persist upward. Clast size is in places as large as 15 cm, but commonly ranges to 5 cm. Sandstones are texturally immature. Sand composition is dominated by feldspar and volcanic lithic fragments, with mica common. Paleocurrent indicators in cross-laminated sandstone indicate flow to the north, northeast, and east. Bedding architecture indicates a braided, sandy floodplain with gravel-filled channels. Fine-grained intervals are mostly covered. High in the measured section, the strata contain more sand, and abundant soft-sediment load structures indicate a return to dominantly lacustrine conditions. Paleocurrent indicators continue to be dominated by northwest- through northeast-directed flow throughout the section.

Retrace route to U.S. 40 in Hot Sulphur Springs and return east across the Breccia Spoon syncline to the Windy Gap Wildlife Observation Area just east of the junction with CO 125 (road to Walden). This is the Day 1 lunch stop.

Toward Willow Creek Pass

Exit Wildlife Observation Area on U.S. 40 westbound (left) and turn immediately north (right) on CO 125 toward Willow Creek Pass and Walden. The first mile of the road climbs steadily through poorly exposed brown-weathering volcanic sandstone and cobble conglomerate of the Middle Park Formation that is the down-faulted east limb of the Granby anticline on the flank of the Breccia Spoon syncline (Fig. 4). The road crosses this fault and follows a strike valley in Pierre Shale (yellow-brown sandstone ledge on left is the Hygiene Sandstone Member) over a gentle divide and then enters the Willow Creek drainage just beyond the entrance to the C Lazy U Ranch.

The highway crosses the steeply dipping Windy Gap Volcanic Member at the dark cliffs flanking the water gap of Willow Creek. Within less than 0.5 mi, the attitude of bedding flattens from ~75° to 25° or less. Granitic and gneissic clasts are present in minor amounts in the conglomerates of the Windy Gap Volcanic Member, but are present in much greater proportions in sandstone and conglomerate beds up-section. For the next several miles along CO 125, the Middle Park Formation consists of interbedded fluvial sandstones and siltstones with locally prominent cross-stratification. The more highly arkosic sandstone beds are pale orange-tan in color whereas the more volcaniclastic and mixed-source beds are primarily medium-brown or brown-gray in color. Fossil leaves, seeds, flowers, twigs, and small logs are preserved sporadically throughout this section.

Continue northward up the Willow Creek valley (also up-section in the Middle Park Formation) past the Buffalo Creek junction and the Denver Creek Campground. Approximately 1.0 mi farther upstream where the valley floor widens at a tributary canyon on the west (left), stop alongside the road.

STOP 1-3: MIDDLE PARK FORMATION IN WILLOW CREEK VALLEY

The Middle Park Formation is somewhat different from Stop 1-2 in several aspects here on the east limb of the Breccia Spoon syncline. The top of the Windy Gap Volcanic Member here is more gradational than on the west limb where it is a sharp contact, and the transitional section includes volcaniclastic deposits interbedded with sandy intervals. This transitional interval thickens to the south, where it has been mapped as a separate unit: the informal breccia of Marietta Creek (Izett, 1968). Up-section, the strata are mainly sandstones that are dominated either by volcanic debris, including pumice, or by arkosic material derived from crystalline basement. The section has less conglomerate upward, and sandstone intervals display channels, tabular and trough cross-beds, and architecture consistent with sinuous river deposits. Paleocurrent indicators record flow mainly to the west here, toward the inferred axis of the basin.

The east limb sections, then, contrast with the west limb in several aspects. The west limb is dominantly lacustrine and floodplain deposits, whereas the east limb is mainly fluvial. The west limb has a sharp transition at the top of the Windy Gap Volcanic Member, but the east limb has intercalated facies. The west limb sandstone section above the Windy Gap is mostly arkosic; the east limb has nearly equal amounts of arkosic and volcanic sandstone. Pending better age control, we cannot yet precisely correlate the sections on opposing sides of the syncline.

Paleobotany of the Middle Park Formation

The Middle Park Formation contains plant compression-impression fossils throughout (Izett, 1968) but the localities that exhibit the best preservation are near the top of the formation. The earliest reports of fossil plants from the section are from the Hayden Survey in 1869 (Hayden, 1869), which listed fossil sites along the north side of the Colorado River on Mount Bross in the vicinity of Hot Sulphur Springs at the base of the formation. Work by a master's student at the University of Colorado, Boulder, revealed new sites in the upper portions of the Middle Park near Denver and Kauffman Creeks (Barnhart, 1941). The Denver Museum of Nature & Science (DMNS) reoccupied several of these sites and collected more than 1,500 leaf, seed, and flower fossils from them. Ongoing work by DMNS is describing and analyzing the fossil flora at this level in the Middle Park Formation.

The most productive plant horizons are in beds composed of fine- to medium-grained sandstone with thin volcanic ash-rich mudstone interbeds. The beds are characterized by planar to sporadically convolute bedding and ripple cross-stratification. Fossils in these beds consist of coalified logs, leaves (on bedding planes and across them), and horsetail stems preserved in growth position penetrating the ash-rich horizons (Fig. 5). Based on the combination of sedimentary structures, lithology, and fossil associations, we interpret these beds to be crevasse-splay deposits.

Palynological analysis of the Middle Park Formation by Izett (1968; Izett et al., 1963) suggested that it was primarily Paleocene in age but the Windy Gap Volcanic Member might be as old as Maastrichtian based on a fossil pollen sample from immediately above the contact with the upper member of the Pierre Shale. DMNS reanalyzed two pollen slides from this sample suite and identified Paleocene pollen zone P3 (ca. 64.5–59 Ma; Nichols, 2003, 2009) indicator species of the Western Interior Basin pollen zonation. These results indicate that the Late Cretaceous pollen reported by Izett was reworked (Miller et al., unpublished data). In conjunction with the analysis of the leaf megaflora, DMNS also sampled the ash-rich beds for palynomorphs and found pollen zone P5 of late Paleocene age (ca. 58–57 Ma). DMNS, in collaboration with Massachusetts Institute of Technology, is working to date the ash-rich fossil leaf beds near Kauffman Creek by determining a reliable volcanic zircon $^{206}Pb/^{238}U$ age (Miller et al., unpublished data).

The Middle Park megaflora contains lycopsids, sphenophytes, ferns, conifers, monocots and broad-leafed angiosperms. In general, the megaflora is typical of late Paleocene floras in Laramide basins (Brown, 1962); however, it also contains a few

Figure 5. An *Equisetum* sp. stem preserved in growth position; DMNH loc.3218, DMNH 30800. The specimen was prepared from the surrounding matrix. Note the cross-stratification of the matrix attached on the lower left-hand side of the specimen. Scale bar equals 1 cm.

species that have not been described elsewhere. Some of the common, well-known components are *Onoclea hesperia* Brown (1962; fern); *Elatocladus* sp. (taxodiaceous conifer); and *Equisetum* sp. (horsetail; Figs. 5 and 6; Miller et al., 2006). The common broad-leafed angiosperms include *Cercidiphyllum genetrix* (Newberry) Hickey (1977), *Platanus raynoldsii* (Newberry, 1868); and *Cornophyllum newberryi* (Hollick) McIver and Basinger (1993; Fig. 6; Miller et al., 2006).

Over the Rabbit Ears Range

Continue northward on CO 125 along Willow Creek drainage; at the junction with the Stillwater Pass road, continue on CO 125 for ~4 mi. Note the prominent, vertical, intrusive dike that is well exposed on the east (right) side of the roadway. This is one of many late Oligocene dikes connected with the Radial Mountain intrusive center and other subvolcanic conduits in the Rabbit Ears Range (all ca. 33–28 Ma; Marvin et al., 1974). More than a dozen small intrusive stocks are distributed in an east-west alignment between the Park Range block on the west and the Front Range block on the east (Fig. 3). At its eastern end, the alignment of Oligocene intrusive centers changes to a northerly trend through the Never Summer Mountains in the northwestern corner of Rocky Mountain National Park (Cole and Braddock, 2009). Gently inclined volcanic ash beds, lava flows, and volcaniclastic sediments are preserved in the western Rabbit Ears Range (Izett, 1968) and the northern Never Summer Mountains (Cole et al., 2008), but nearly all have been eroded from the central part of the Range traversed by CO 125.

Willow Creek Pass

Willow Creek Pass (9621 ft) marks the Continental Divide between Colorado River drainage to the south and North Platte River drainage to the north. It is also the physiographic boundary between North Park (to the north) and the irregular lowlands collectively named Middle Park to the south (Fig. 1). The Paleocene-Eocene structural and sedimentary basin that we are discussing on this field trip is continuous beneath the younger volcanic features that define the crest of the Rabbit Ears Range. That is why we have designated the older feature the Colorado Headwaters Basin, so that it is more clearly distinguished from modern physiography. The Continental Divide also marks the arbitrary boundary between the Middle Park Formation to the south and the Coalmont Formation to the north. The lower Tertiary section in the Rabbit Ears Range has not been investigated in detail, although the section is believed to be continuous between Middle Park and North Park. We discuss the relations between the two formations in further detail during the trip, but much remains to be learned regarding the sedimentary history of the Colorado Headwaters Basin.

Note that as CO 125 descends into the North Park basin, the sandstones and siltstones dip a little more steeply than the roadway and so we continue to climb up in the stratigraphic section. Roadcuts expose additional Oligocene porphyry dikes intruded into fluvial sandstones of the Paleocene and Eocene Coalmont Formation (Tweto, 1976).

Continue northward along CO 125 as the highway flattens and trends toward the northwest through thick stands of lodgepole pine forest that have been heavily damaged by pine-bark beetle infestation over the last decade. Just west of Rand, stop along the side of the road for a panorama of the North Park basin.

STOP 1-4: NORTH PARK OVERVIEW AT RAND

North Park is a large, oval, physiographic lowland surrounded by Laramide block uplifts. The basin floor measures ~40 mi north-south and ~30 mi east-west. The general elevation of the basin floor is ~8200 ft and the summits of the surrounding mountains are ~12,000 ± 1000 ft. North Park is the headwaters of the North Platte River and its major tributaries Grizzly Creek, Illinois River, Michigan River, and the Canadian River. All of the surrounding ranges were glaciated during Pleistocene and Holocene time, and these major rivers are flanked by flights of alluviated terraces that formed during times of major glacial outwash.

Early settlers in the region took advantage of the flat terrain and abundant stream flow by clearing sagebrush from the terrace surfaces and irrigating to grow hay. They also harvested timber from the surrounding mountains, ran cattle, and mined coal from the Coalmont Formation in several localities. Coal production ceased in the 1990s due to cheaper, more abundant sources in Wyoming mines. Today, the economy of the North Park area is driven by year-round recreational tourism in addition to hay and cattle production, hunting, and fishing. Salvage logging in the pine-beetle–killed areas is increasing, as is stove-pellet production from reclaimed timber.

Structural Setting

Structurally, the North Park (Colorado Headwaters Basin) basin owes its origin to Laramide uplift of the Proterozoic basement in the surrounding mountain ranges, and related subsidence of Proterozoic basement beneath the basin floor. Faults that were active during Paleocene uplift-subsidence have not been affirmatively identified and may be largely buried beneath the Coalmont Formation strata. Most of the basin margin today on the east (Front Range–Medicine Bow Mountains) and on the west (Park Range) is marked by a tilted but unfaulted contact between the Proterozoic crystalline rocks and the Permian-Triassic sedimentary sequences of the Chugwater Formation, Forelle Limestone, and Satanka Shale (Figs. 3 and 4). All of this tilting seems to postdate the Coalmont Formation, as inferred from the general parallelism of bedding in the Coalmont and the sandy middle unit of the underlying Pierre Shale (Fig. 2). High-angle reverse faults and so-called "thrusts" have been mapped along parts of the basin margins (e.g., Never Summer thrust of Gorton (1953) and Ward (1957)), but most of the deformation can be explained as systems of short, en echelon steep reverse faults that accommodated

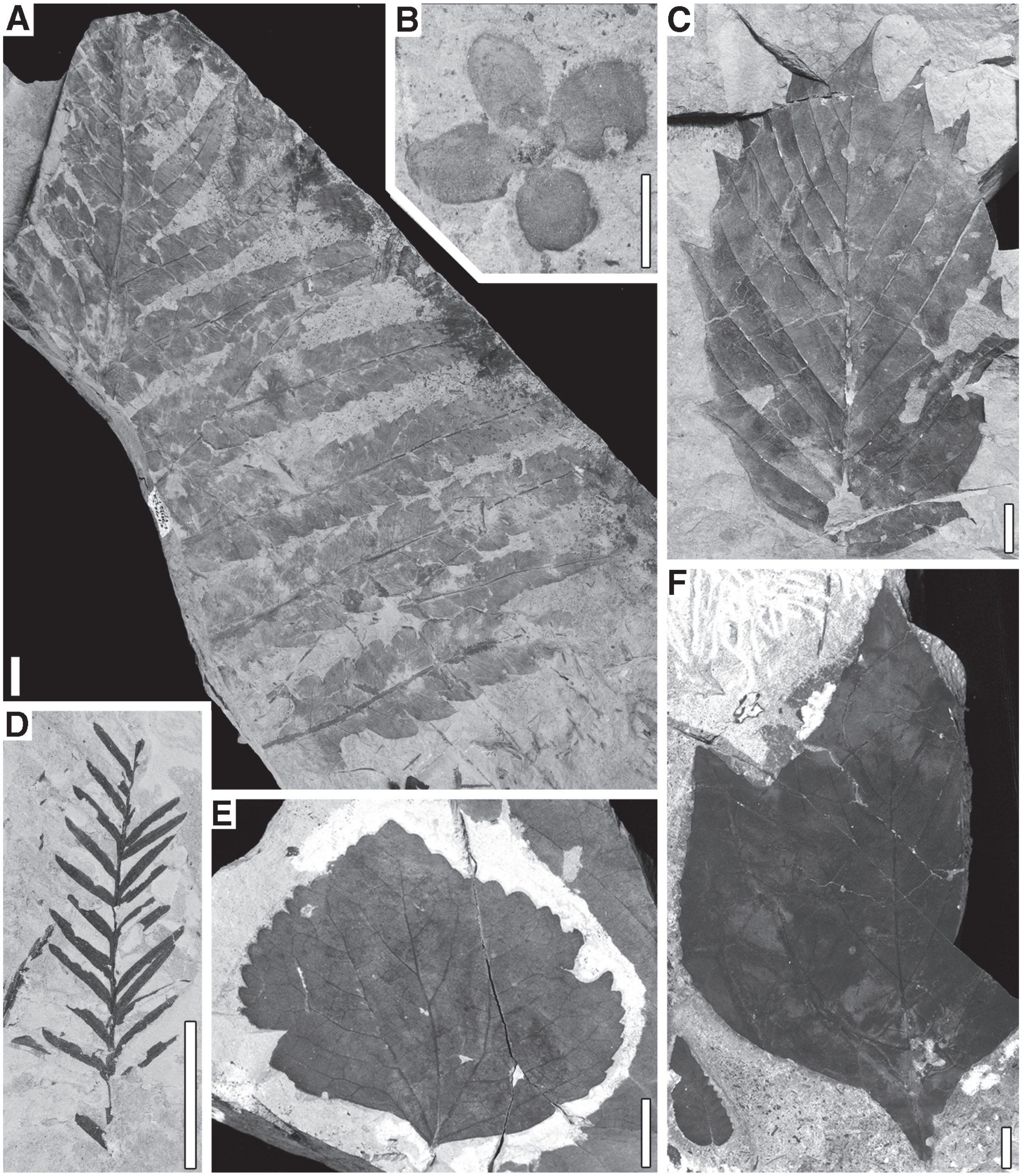

Figure 6. Some plant megafossils from the Middle Park Formation. (A) *Onoclea hesperia* Brown (1962), DMNH loc.1304, DMNH 27613 (fern); scale bar equals 1 cm. (B) An unidentified flower, DMNH loc. 1304, DMNH27593; scale bar equals 1 cm. (C) *Cornophyllum newberryi* (Hollick) McIver and Basinger (1993), DMNH loc.1304, DMNH30801; scale bar equals 1 cm. (D) *Elatocladus* sp. (taxodiaceous conifer), DMNH loc.1304, DMNH27618; scale bar equals 1 cm. E. *Cercidiphyllum genetrix* (Newberry) Hickey (1977), DMNH loc.1304, DMNH27621; scale bar equals 1 cm. F. *Platanus raynoldsii* Newberry (1868), DMNH loc.3235, DMNH27623; scale bar equals 1 cm.

the uplift of Proterozoic rock on the basin margins (Cole et al., 2010). The north end of the Colorado Headwaters Basin is defined by the east-west Independence Mountain (thrust) fault (Steven, 1960; Blackstone, 1975). The trend of this fault is anomalous in this region, and the fact that it appears to truncate the Coalmont Formation without folding it suggests it might be a much younger (post-Laramide?) fault that is relatively steep.

Stratigraphic Overview

The continental fluvial and lacustrine sandstones, siltstones, and coal deposits of the Paleocene-Eocene Coalmont Formation in the North Park basin were defined by Beekly (1915) and descriptions were refined by Erdmann (1941). The Coalmont contains arkosic cobble and boulder conglomerates near the west and northeast basin margins and mafic-intermediate volcanic-clast conglomerates (equivalent to the Windy Gap Volcanic Member of the Middle Park Formation) at the southeast basin edge and south of Rand. Hail and Leopold (1960), followed by Hendricks (1978) and Stands (1992), refined both the stratigraphy and chronology of the Coalmont Formation with pollen biostratigraphy. Flores (1990) documented lacustrine delta complexes in the Coalmont, and Roberts and Rossi (1999) prepared a summary of depositional environments, coal distribution, and lithologic variations in the Coalmont Formation.

Due east of this location (Stop 1-4) on the skyline, the gray, timberless ridges of the Never Summer Mountains in northwestern Rocky Mountain National Park consist of late Oligocene intrusive rocks that are interpreted to be the conduits for volcanic centers that built on the landscape at that time (Cole et al., 2008). These intrusive and volcanic rocks (mostly calc-alkaline and ranging from basalt to high-silica rhyolite) are designated the Braddock Peak intrusive-volcanic complex (Cole and Braddock, 2009). They are similar in composition and age to the intrusive-volcanic rocks of the Rabbit Ears Range.

These volcanic edifices were eroded as they formed, producing boulder and cobble conglomerate deposits that are designated the North Park Formation (Montagne, 1957; Hail, 1965). This coarse, fluvial unit is chiefly preserved in the North Park syncline that traverses the valley from east to west (Fig. 4), and in the Saratoga Valley north of the Wyoming-Colorado state line. Looking to the northeast from here, the forested summit of Owl Mountain shows a gently inclined, upper Oligocene rhyodacite lava flow above the partially eroded Coalmont Formation near the top; this flow is overlain by North Park Formation boulder conglomerate and another, similar rhyodacite lava flow. Farther west along the low ridge that marks the south limb of the North Park syncline, the eroded Coalmont is overlain by a few meters of lower Oligocene White River Formation (Montagne, 1957) and by a pink-weathering rhyolite ash-flow tuff that was erupted from the Braddock Peak complex at 28.0 Ma (Cole et al., 2008). The mixture of Proterozoic crystalline-rock clasts with porphyritic, intermediate and rhyolitic clasts eroded from the Rabbit Ears Range and Braddock Peak complex has served to identify the North Park Formation across the landscape. The distribution of North Park gravels indicates they may once have filled the North Park valley to a depth of more than 1000 ft. The ancestral North Platte River drainage that traversed the ultimate accumulation surface of the North Park Formation (probably late Miocene–Pliocene time) was later superimposed during Pliocene-Pleistocene regional incision (Steven et al., 1997). Today, the North Platte and Laramie Rivers flow through steep-walled canyons that were incised into Proterozoic basement along drainages that were superimposed from the North Park surface above.

WALDEN, COLORADO

Walden is the governmental seat of Jackson County, Colorado, which celebrated its centennial in 2009. The reason Jackson County was established so late (33 years after Colorado statehood) is an interesting blend of geography and politics. When counties were established in the Colorado territory in 1861, both Larimer County (to the east) and Grand County (to the south) claimed the valley. No one paid much attention because few settlers resided in North Park. As the valley became settled and productive (timber, hay, coal, cattle), Grand County became interested in collecting tax revenue from the area. Larimer County filed suit in Colorado Court to claim that North Park should be included in their jurisdiction because the western county boundary was described in the original legislation as "the crest of the snowy range." Larimer County claimed that language meant the crest of the Park Range west of North Park, whereas Grand County asserted it meant the crest of the Medicine Bow Mountains east of North Park.

The Colorado Supreme Court heard the case in 1886 and ruled in favor of Larimer County over the objections of the North Park residents. For the next few years, North Park-ers were forced to conduct county business in Fort Collins in the eastern foothills of the Front Range. There was no established trail or road down the Cache la Poudre River canyon (Fig. 1), so getting to Fort Collins involved a three-day trip from Walden, northeastward over the Medicine Bow Mountains to Laramie, Wyoming, and then southeast along the North Fork of the Cache la Poudre River (equivalent to Highway 287; Fig. 1). The railroad was extended into North Park during this time to handle the coal production (making the journey less arduous), but residents of Walden and vicinity had decided it was time to have a county of their own. With some hard-won support in the Colorado legislature, Jackson County was finally established on 5 May 1909 to encompass all of the North Park valley and the surrounding mountain ranges to their drainage divides.

DAY TWO. NORTH PARK

Travel north of Walden on CO 125 ~0.5 mi across the Michigan River and turn east (right) on a dirt track just below the fluvial terrace occupied by the Jackson County Airport.

STOP 2-1: LACUSTRINE DELTA COMPLEXES IN THE COALMONT FORMATION

The following synopsis of the Coalmont Formation is excerpted from the summary by Roberts and Rossi (1999), as well as Flores (1990) and Stands (1992). More than 80 pollen samples from all across the North Park area provide a rough chronology of sedimentation in the northern part of the Colorado Headwaters Basin. The oldest Coalmont Formation beds are middle Paleocene (possible lower Paleocene, locally) and they seem restricted to the eastern part of the valley where they disconformably overlie the Upper Cretaceous sandy middle part of the Pierre Shale (Fig. 2). Volcaniclastic sandstone/conglomerate units (related to the Paleocene volcanic edifices that were sources of the Windy Gap Volcanic Member and volcanic sandstones in higher parts of the Middle Park Formation) appear to be restricted to the southern and southeastern parts of the North Park valley. Two economically productive coal beds in this area (Sudduth and Capron coals) are interbedded with arkosic sandstone and carbonaceous siltstone in the lower 2000 ft of the Coalmont Formation in the area of the McCallum anticline (Fig. 4). The uppermost Coalmont in this area is upper Paleocene and interpreted to be dominantly lacustrine; younger parts of the formation were removed by subsequent erosion in this area.

In these bluffs below the airport, thick cross-bedded sandstones are exposed that make up part of a lacustrine delta complex. Planar- and ripple-bedded medium-grained sandstones form large (>10 m) foresets, overlying darker, finer-grained strata. Wood debris is common on some bedding surfaces. Plane laminae indicate upper-flow-regime conditions; at this grain size, that indicates flow velocity exceeding 1 m/s. The sandstone is micaceous and immature; the quartz and feldspar grains are angular. Iron concretions are present along some bedding horizons. The low-angle discordance between beds suggests progradational delta lobes. This locality is interpreted as a south-prograding sandy delta.

Return south through Walden on CO 125. At the south end of town, the highway turns west (right) on the corner by the cemetery and descends from the fluvial terrace to cross the Illinois River. Continue straight ahead on County Road 12W in the direction of Lake John and the Delaney Butte Lakes State Wildlife Area. Continue west ~4.5 mi to a gentle ridge crest where the road begins to descend to the North Platte River valley.

STOP 2-2: STRUCTURAL STYLE OF POST-COALMONT DEFORMATION IN NORTH PARK

Paleocene and lower Eocene sediments of the Colorado Headwaters Basin filled the structural sag (possibly a graben) to a depth estimated to exceed 9000 ft (Hail, 1965, 1968). Coarse conglomeratic units preserved on the margins of the basin indicate that both volcanic and crystalline-basement source areas were rapidly eroded and transported to the Colorado Headwaters Basin (now the Middle Park and Coalmont Formations). Internal stratigraphy of these units is not sufficiently known to evaluate whether tilting accompanied subsidence. Relatively minor angular unconformities have been documented or suspected in a few areas, but they do not appear to be widespread. Persistent, thick carbonaceous siltstones (probably floodplain and lacustrine) and locally thick coal beds in the Coalmont Formation indicate only minor intrabasin tilting (Roberts and Rossi, 1999).

Deposits of the Colorado Headwaters Basin were deformed by folding and faulting after early Eocene time, but the deformation appears limited to a number of spatially restricted structures. On a regional scale, the Colorado Headwaters Basin is a broad, open syncline with gentle flank-dips (~15° to 35°) and an axis that plunges gently toward the center from the north (Walden syncline) and from the south (Breccia Spoon syncline; Fig. 4). This structure persists for nearly 70 mi south of the Colorado-Wyoming State line. The more local structures superimposed on this broad syncline consist of narrow, asymmetric, faulted anticlines (and flanking synclines) that form north-northwest–trending, en echelon deformed belts. These faulted anticlines show great structural relief, typically raising Proterozoic basement more than 10,000 ft against Coalmont or Middle Park Formations (Wellborn, 1977).

Narrow Faulted Anticlines

Looking northward, an elongate, narrow ridge illustrates several elements that appear to be common to this style of deformation. The ridge consists of three separate, en echelon fault blocks, each of which brings crystalline basement to the present-day surface in fault contact with Coalmont Formation or Pierre Shale. From south to north, they are Delaney Butte, Sheep Mountain, and Boettcher Ridge (Fig. 4). Each is an asymmetric, faulted anticline with westward vergence and south-trending plunge. The faults in these structures dip moderately to steeply eastward, and cross-cutting relations indicate they formed sequentially from south (Delaney Butte) to north (Boettcher Ridge). Minor subsidiary folds are mapped in the Paleozoic-Mesozoic strata on the more gently inclined eastern limb of these anticlines. The minor folds probably formed by bedding-plane slip in response to tilting above the Proterozoic basement (Wellborn, 1977). The western limbs of the anticlines are much steeper and locally overturned to the west (Hail, 1968).

In northeastern North Park, the geologic map pattern expresses a series of steep-limbed, narrow anticlines and synclines that involve the basal Coalmont Formation and the eroded top of the Pierre Shale (Kinney, 1970; Tweto, 1976). No thrust/reverse faults are exposed, but exploratory drilling on the anticlinal crests shows that the structural culminations overlie steep reverse faults that dip westward and show eastward vergence (Wellborn, 1977). Similar faulted anticlinal structures are present in southern North Park in the vicinity of Buffalo Ridge (Fig. 4; Mark, 1958; Wellborn, 1977). This structure displays thousands of feet of dislocation, raising the base of the Coalmont Formation to the present-day ground surface. The fact that the basal Coalmont here in the middle of the Colorado Headwaters Basin rests on Niobrara Formation or Dakota Sandstone (rather than Pierre Shale) indicates this structure may have been active prior to Coalmont deposition as well. A similar interpretation is inferred for the Mount Bross fault (Stop 2-5, described below).

An interesting feature of many of these structures in the Colorado Headwaters Basin is that they are generally parallel to the long-axis of the basin but that their sense of vergence is from the basin toward the flanking basement uplifts. This geometry can be described as "out-of-basin faulting" and is a style shown in numerous Laramide structural basins. The fact that these structures have limited strike length and yet display great stratigraphic displacement indicates that they are likely secondary structures related to flexing of the relatively rigid Proterozoic basement. These steep reverse faults propagated through the crystalline basement while the overlying, deformable stack of sandstones and shales reacted passively to fault displacement with draped folds (see Stearns, 1978).

Continue west on CR 12W to CR 18 and the North Platte River valley. Turn south on CR 9 (dirt) to the junction with CO 14 (paved). Turn southwest (right) at the intersection. The road rises gently through rolling topography and crosses a roadcut that exposes a few tens of feet of white-gray, poorly bedded tuffaceous mudrock, siltstone, and lacustrine limestone of the lower Oligocene White River Formation (Montagne, 1957).

North Park Formation

The next roadcuts to the south show abundant, well-rounded cobbles and football-sized boulders of Proterozoic and volcanic rock. These fluvial gravels represent the upper Oligocene and Miocene North Park Formation, which is mostly preserved here in the core of the northwest-trending North Park syncline (Montagne and Barnes, 1957; Tweto, 1957, 1976). The North Park Formation contains abundant clasts derived from intrusive-volcanic rocks emplaced in the Never Summer Mountains and in the Rabbit Ears Range at about the same time. The North Park Formation is interpreted to have filled the North Park Basin to a depth of as much as 1000 ft prior to regional uplift, regional incision, and integration of the North Platte River drainage in late Miocene and Pliocene time (Steven, 1956; Blackstone, 1975; Mears, 1993).

The gentle crest of the roadway to the south crosses the axis of the North Park syncline. Intermittent roadcuts and outcrops down toward the floodplain of Grizzly Creek show more boulder conglomerate of the North Park Formation. Lower slopes are chiefly the eroded top of the Coalmont Formation, which is mostly covered with bouldery colluvium. Across Grizzly Creek, CO 14 continues south-southwest on a Pleistocene fluvial terrace for several miles to a road junction at the former townsite of Hebron, Colorado. Recent (2008–2010) oil exploration in this area and southward has successfully produced from deep strata of the Niobrara Formation using directional drilling.

Coal at Coalmont

The road to the west of Hebron leads to the historic coal mining center of Coalmont (Fig. 1; presently abandoned). The coal mined here came from the upper member of the Coalmont Formation (Hail, 1965; Hendricks, 1978; Stands, 1992) that is Eocene in age. The prominent Riach coal bed (pronounced "ry-ack"; named for early homesteaders) is lenticular, ~25–85 ft thick, and dips gently eastward. The coal was mined at the surface and in underground workings that followed the Riach and other seams downhill to the east. Numerous northwest-trending normal faults traverse the area and offset the coal seams by as much as 100 ft, complicating the underground development (Roberts and Rossi, 1999).

CO 14 makes a turn toward the west, following the Grizzly Creek valley, and climbs gently toward Muddy Pass and the Park Range on the skyline. Park alongside the highway to examine the lower Coalmont Formation on the western side of the basin.

STOP 2-3: LOWER COALMONT FORMATION ON THE NORTHWESTERN MARGIN OF THE COLORADO HEADWATERS BASIN

About 0.5 mi west of this stop, the basal Coalmont Formation rests on eroded beds of the lower Pierre Shale and, locally, on the Niobrara Formation. The basal Coalmont generally lies on younger parts of the Pierre Shale to the north and south of this locality, indicating that this particular area was structurally high (and perhaps structurally rising) during initial Coalmont sedimentation. Several miles to the east at Buffalo Ridge, basal Coalmont rests on Upper Cretaceous Niobrara Formation and Lower Cretaceous Dakota Sandstone with angular unconformity. These relations also indicate pre-Coalmont uplift and tilting.

Alternatively, this region may have been high and on-lapped by Coalmont beds, but present data do not provide enough age-resolution on Coalmont deposition to distinguish between the two hypotheses. For the most part, pollen data indicate the lowest Coalmont Formation here is late Paleocene in age (Stands, 1992; Roberts and Rossi, 1999) and thus is slightly younger than the oldest Coalmont beds on the eastern side of the Colorado Headwaters Basin.

Sedimentology of the Lower Coalmont Formation

Outcrops of the Coalmont Formation here at Grizzly Creek, in *southwestern* North Park, are near the base of the section, but are anomalous for this stratigraphic position in that they do not contain conglomerate. The strata are dominated by 2-m-thick, cross-bedded intervals of poorly cemented arkosic sandstone and grit. Intervening finer-grained beds are thin-bedded and ripple cross-laminated. The grains are sub-angular to sub-rounded, and include quartz, feldspars, micas, mafic minerals and lithic clasts. The dominant cross-bedded intervals are interpreted as point-bar sets recording a channel-dominated meandering fluvial system; the finer, thin-bedded strata represent floodplain sands. These rocks were deposited by a high-sinuosity sandy river, with meanders 100s of meters in amplitude. Paleocurrents, based on the down-dip direction in three different point-bar sets here, flowed east-northeast.

The basal Coalmont Formation in *northwestern* North Park (CR 6 near Dead Horse Hill; DHH, Fig. 3) comprises coarse sandstone and sandy conglomerate interbedded with fine-grained sandstone and siltstone. The granule and pebble conglomerate is channelized and lenticular, with tabular, gravelly crossbeds common. Conglomerate commonly fills channels cut into the finer-grained beds. Maximum clast size is 20 cm, and 10-cm clasts are common. The finer-grained beds include sandstone/mudrock couplets and contain loading structures, soft-sediment injection features, and plant debris. The most reliable paleocurrent measurements are from the tabular foresets, especially where these are continuous laterally. Here, downdip directions on tabular bar foresets record a dominant paleocurrent direction toward the east-southeast. Clast compositions are consistent with a source to the west in the Park Range; clasts are 73% granitoids, 24% metamorphic rocks, and 3% sedimentary rocks (the subjacent Pierre Shale). The Coalmont here is interpreted as a gravelly and sandy, low-sinuosity river ~1 m deep. The floodplain was dominated by sandy splays and mud drapes.

Up-section, the strata are coarser with boulder conglomerate interbedded with local thin, coarse-grained sandstone layers in places. The cobbles are commonly 10–20 cm, and the boulders are locally up to 2 m across. The clasts are dominantly granitic (63%) and metamorphic (36%), with minor sandstone blocks derived from the underlying Coalmont Formation (1%). Here, down-dip directions on tabular bar foresets record paleocurrent directions toward the east-northeast. These rocks are interpreted as gravelly fluvial deposits with well-formed bar foresets; the cobble horizons parallel the sandstone beds, indicating high flow velocities and a reliable paleocurrent direction. These rocks are interpreted to represent a braided river 1–2 m deep and dominated by coarse-grained longitudinal bars. Paleocurrent indicators in fluvial deposits near the top of the exposed section trend generally east.

Muddy Pass

Continue southwest and west on CO 14 toward Muddy Pass. Isolated hills to the southeast and west of the highway primarily consist of late Oligocene intrusive rocks related to the Rabbit Ears Volcanics (Izett, 1968) that intruded through softer rocks of the Coalmont Formation. The skyline to the southwest displays the distinctive double-tower profile of Rabbit Ears Peak. At Muddy Pass (8772 ft), CO 14 joins with U.S. 40, which continues westward over Rabbit Ears Pass and down to Steamboat Springs.

Turn southeast (left) and descend Muddy Pass on U.S. 40 toward Kremmling. The highway follows the south-flowing Muddy Creek along a strike valley in the easily erodible Pierre Shale. Foothills to the west expose the east-dipping lower part of the Phanerozoic section (down to Jurassic Morrison Formation) that overlies Proterozoic gneisses and granites on the western skyline along the low crest of the Gore Range (Izett and Barclay, 1973). For the most part, the margin of the Gore Range is unfaulted at this structural level, similar to the general conditions along the eastern front of the Park Range on the western margin of North Park.

The high ground to the east of U.S. 40 exposes basal beds of the Middle Park Formation overlying the sandy middle part of the Pierre Shale. Elsewhere toward the south, the near skyline consists of upper Oligocene Rabbit Ears Volcanics resting directly on the Pierre (due to post-Middle Park erosion). About 5 mi south of Muddy Pass, U.S. 40 passes a conical hill to the east (Whiteley Peak) that exposes brownish, blocky rubble of pyroxene quartz latite; this is one of several subvolcanic intrusive bodies that were conduits for eruptive rocks of the Rabbit Ears Volcanics (Izett and Barclay, 1973).

STOP 2-4: GIANT LATE CRETACEOUS AMMONITES IN THE UPPER PIERRE SHALE

The excellent exposures of the Pierre Shale near Kremmling represent the most complete section of the formation in the North, Middle, or South Park Basins of Colorado (Izett et al., 1971). Here the Pierre Shale rests conformably on the Niobrara Formation and is, at its base, early Campanian in age. The top of the section is within in the *Baculites eliasi* zone (ca. 72–70.6 Ma) and is unconformably overlain by the Middle Park Formation (Cobban et al., 2006), indicating that less section was eroded here before deposition of the Middle Park compared to the middle of the Breccia Spoon syncline to the east. The section contains abundant fossiliferous concretions, which Izett et al. (1971) used to correlate these beds to the section near Hamilton, Colorado, ~70 mi to the west and to the section near Boulder, Colorado, ~60 mi to the east.

Though there are fossils throughout the section, the Pierre Shale is famous here for the Kremmling Cretaceous Ammonite Research Area, which hosts a super-abundance of giant ammonites. This unique, world-class fossil locality is protected by the Bureau of Land Management and is considered an Area of Critical Environmental Concern as well as a Research Natural Area. The State of Colorado has labeled the site a Colorado Natural Area.

Location

Access to the site is overseen (2010) by Frank Rupp at the Kremmling office of the BLM. To reach the site, turn left (east) off U.S. 40 ~9 mi south of Whiteley Peak (mile marker 173.9) onto CO Hwy 25 (dirt). After crossing Muddy Creek, bear left (northeast) on CR 26 for ~3.5 mi to an unmarked dirt road. Turn left (northwest) onto the unmarked road and follow for about one mile. Park at the gate marked by the BLM "Kremmling Cretaceous Ammonite Research Area" and hike up the hill to where the ammonites are exposed on a broad gentle slope of the Pierre Shale.

Paleontology at the Cretaceous Ammonite Research Area

The exceptionally preserved giant ammonites, *Placenticeras meeki*, are as much as 30 inches in diameter. They are in large concretions (Fig. 7) in a sandy interval in the Pierre interpreted as nearshore deposit in the *Baculites compressus* Zone of late Campanian age at ca. 73 Ma (Cobban et al., 1992, 2006). Most of the ammonites at the surface were collected before the area was protected by the BLM but split concretions that show the external molds of more than 300 shells are strewn across the site. Specimens of inoceramid clams and *Baculites* are also common at the site. Though several interpretations of the taphonomy of the locality have been suggested the most favored scenario is that the site was a breeding ground for the ammonites (Johnson, 1999). This interpretation is bolstered by the fact that ammonites are typically sexually dimorphic with the females being much larger than the males. At the Kremmling site, the large female shells are much more common than the small male shells (Fig. 7A). If there had been an equal number of large and small shells and thus no selection based on sex, a catastrophic event that triggered a mass death would be more likely (Johnson, 1999).

The horizon that contains the giant *Placenticeras meeki* specimens also shows an exceptionally diverse marine fauna with more than 100 species of fish, gastropods, crabs, lobsters, brachiopods, clams, snails, *Baculites*, and four or five more species of ammonites including rare subtropical to tropical heteromorphic forms (Cobban et al., 1992). As such, the Kremmling Ammonite beds represent one of the more unusual fossil occurrences in North America.

Wolford Mountain

Return to U.S. 40 and turn south (left). Wolford Mountain Reservoir (Muddy Creek drainage) appears on the east (left). The prominent rugged hill of Wolford Mountain is conspicuous on the eastern skyline because its forested upper slopes contrast with grassy, treeless slopes on the lower half of the peak. The vegetation change coincides with a flat-lying fault that separates Proterozoic gneiss above from Pierre Shale below. Wolford Mountain has been interpreted as an isolated klippe on the margin of the west-vergent Williams Range thrust fault (Tweto, 1957; Izett and Barclay, 1973). This interpretation is supported by other outcrop relations nearby to the east where Proterozoic rock overlies Upper

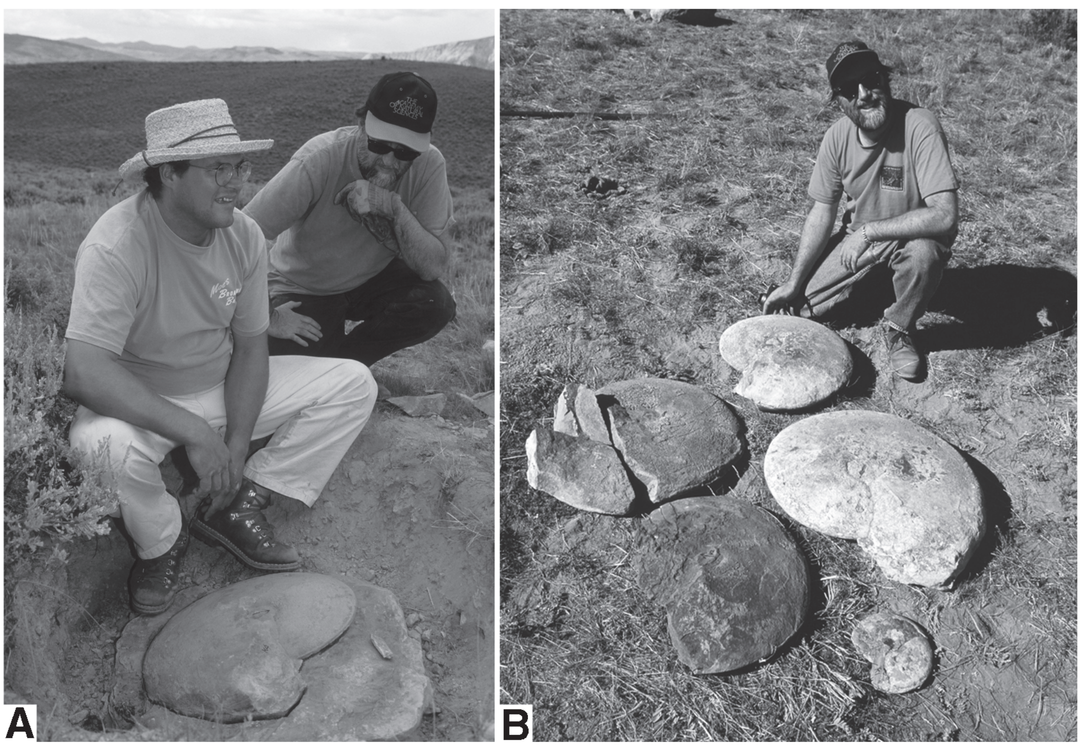

Figure 7. (A) Kirk Johnson (left) and Ray Troll (right) pulling a *Placenticeras meeki* shell from a concretion at the Kremmling Cretaceous Ammonite Research Area. Kirk and Ray, along with a team from the Denver Museum of Nature & Science (DMNS) excavated specimens for a museum exhibit. These specimens are now part of the collection at DMNS. Their expedition and the brooding-ground scene they envision is described and illustrated in *Cruisin' the Fossil Freeway: An epoch tale of a scientist and an artist on the ultimate 5,000 mile paleo road trip* (Johnson and Troll, 2007) (photo: Rick Wicker DMNS). (B) Ray Troll shown with four female specimens and one male specimen (smaller specimen, lower right) of *P. meeki* (photo: Rick Wicker, DMNS).

Cretaceous shale along an east-dipping, moderately to steeply inclined reverse fault southward from Kremmling (Fig. 4).

G. Izett (June 2010, oral commun.) reported that Proterozoic rock in the Wolford Mountain block locally overlies conglomerate interpreted to be Troublesome Formation. This evidence (not confirmed at the time of writing) would be consistent with an alternative hypothesis that Wolford Mountain represents a gravity-slide block that was emplaced after Troublesome deposition.

Colorado River Incision

Continue south-southeast on U.S. 40 through Kremmling, crossing the Colorado River. West of here, the Colorado descends through Gore Canyon where the river cuts a steep, deep gorge through the Proterozoic basement core of the Gore Range. This canyon is one of many in the region that provide evidence that the modern drainage developed on a higher-level surface and was later superimposed across older structure as the whole region was uplifted (late Miocene–Pliocene time; Tweto, 1957, 1975; Izett, 1968) and regional drainage incised.

U.S. 40 turns eastward and follows the Colorado River upstream toward Hot Sulphur Springs. Just east of Kremmling airport, the landscape changes to flights of fluvial terraces flanked by gently rolling, treeless slopes that expose multicolored, fine-grained siltstones. This is the type area of the upper Oligocene to Miocene Troublesome Formation (Izett, 1968, 1975) that consists of fine-grained, tuffaceous basin-fill strata known for diverse mammalian fossils. The Troublesome appears to have largely filled preexisting topographic depressions with abundant eolian volcanic material from various local and distant sources, as well as fluvial and alluvial additions from the local landscape.

West of Parshall, U.S. 40 follows the Colorado River upstream through another water gap cut into Proterozoic crystalline basement rock in Byers Canyon. At the eastern end of the canyon, multicolored sedimentary beds of the Jurassic Morrison Formation are exposed, dipping eastward off the Proterozoic basement block, and are overlain by chert-bearing pebbly sandstones of the Dakota Sandstone. The low outcrop/railroad cut on the north side of the Colorado River (and the railroad tracks) shows subhorizontal, arkosic sandstone and conglomerate of the Middle Park Formation overlying the tilted strata of the Morrison and Dakota. Note that the basal Windy Gap Volcanic Member is missing here, although it is plainly in view upstream on the west flank of the Breccia Spoon syncline.

Enter Hot Sulphur Springs and turn diagonally northeast (left) on Park Street. One block north, turn west (left) on West Grand Avenue and cross the bridge over the Colorado River to the hot springs facility.

STOP 2-5: MOUNT BROSS FAULT AT HOT SULPHUR SPRINGS

At this point in the field trip, we return to near where we were on Day 1 at Stop 1-2 looking at the sedimentary architecture of the southern part of the Colorado Headwaters Basin. From that vantage, we observed that the lowest beds of the Middle Park Formation (ca. 61 Ma) consist of thick, coarse, rapidly deposited volcaniclastic conglomerates disconformably overlying the Upper Cretaceous Pierre Shale that had been eroded down to the level of the Hygiene Sandstone Member (ca. 76 Ma; *Baculites scotti zone*). This geologic picture is generally typical of the Colorado Headwaters Basin east of the Mount Bross fault.

Here, ~3000 ft southwest of the Mount Bross fault, a significantly different geologic record is displayed (Figs. 2, 3, 4). In this block, the Pierre Shale is only ~200 ft thick and is overlain by a thin wedge of Windy Gap Volcanic Member that tapers toward the west. The contrasting thickness of the Pierre indicates that the Mount Bross fault (or some precursor in a similar position) was active prior to Windy Gap deposition and was up-thrown by as much as 3000 ft on the south side (that is, by the additional thickness of Pierre Shale stripped). The reduced thickness of the Windy Gap indicates that the block southwest of the Mount Bross fault might have remained high-standing during Windy Gap deposition. In contrast, the current configuration of the two fault blocks indicates that the northeast side of the Mount Bross reverse fault (Upper Cretaceous Pierre Shale) is up-thrown against the southwest side (Paleocene Middle Park Formation). Tweto (1957) and Izett (1968) both noted this reversal of throw as evidence of deformation before and after sedimentation.

Variations in Middle Park Formation across Mount Bross Fault

In addition, the Middle Park Formation above the Windy Gap Volcanic Member south of the Mount Bross reverse fault is distinctly different from the formation on the north side. To the north, the Middle Park consists of mixed volcaniclastic and arkosic sandstones and conglomerates that interfinger through thousands of feet of section. In contrast, the section south of the Mount Bross reverse fault consists of dominantly arkosic sandstones and conglomerates; volcanic clasts are far more sparse in this section than in the Middle Park north of the fault. South of the fault, arkosic Middle Park Formation laps directly onto Proterozoic granite and gneiss. Uraninite deposits were extensively prospected near the unconformity in the mid-1900s (Izett, 1968).

The basal Coalmont Formation at Beaver Creek, south of the Colorado River and southwest of the Mount Bross fault, is dominantly coarse arkosic and volcaniclastic, micaceous sandstone and conglomerate. Bedding is generally 1 m thick or less, and sedimentary structures are mainly trough and tabular cross-lamination. Igneous and volcanic conglomerate clasts are less than 5 cm in diameter. Channels are thin and narrow. Paleocurrent indicators record flow mainly to the north. These strata are interpreted as shallow, low-sinuosity, braided fluvial deposits.

Continue east on U.S. 40 along the Colorado River, traversing the Breccia Spoon syncline to Windy Gap. Pass through Granby and follow the highway as it turns southward and crosses a bridge over railroad tracks and the Fraser River on the east end of town. The broad Granby valley continues southward in a gentle landscape underlain by soft, tuffaceous siltstones of the Troublesome Formation. The Fraser River, on the other hand, tracks upstream to the east where it discharges from a steep, deep, and narrow canyon that was incised into the Proterozoic basement from the Fraser valley beyond to the south.

Follow U.S. 40 southward out of the Granby valley, over a low divide and then downhill through Tabernash and into the Fraser valley. After crossing the railroad overpass, stop on the right-hand side of the roadway opposite the turnoff to CR 83 (Devils Thumb ranch).

STOP 2-6: LATE CENOZOIC HISTORY OF THE FRASER RIVER VALLEY

The Fraser basin is one of three post-Laramide basins formed near the margins of the Laramide Colorado Headwaters Basin (Fig. 3). These basins contain upper Oligocene to upper Miocene Troublesome Formation consisting of weakly cemented to weakly consolidated sediments and locally unconsolidated sand and gravel. The Troublesome Formation is alluvial, eolian, and possibly lacustrine, and was deposited on a surface of considerable relief (Izett, 1968).

In the southern Fraser basin, the Troublesome overlies incipiently welded rhyolite ash-flow tuff (at least 480 ft thick) that was erupted at 27.3 ± 0.1 Ma (Knox, 2005; corrected by E.E. Larson, 2009, written commun.). The tuff partly fills paleovalleys at least as deep as the present-day valley of the Fraser River (Fig. 8). Clasts of the rhyolite tuff are present in channel deposits within the Troublesome Formation.

Sparse outcrops and water wells in the Fraser basin suggest that much of the Troublesome Formation (more than 840 ft thick) consists chiefly of weakly consolidated siltstone with local stream channels that contain interbedded sandstone and conglomerate and locally unconsolidated sand and gravel. The Troublesome seems out of place in this Tertiary basin surrounded by Proterozoic crystalline rocks that produce little silt during weathering. Izett (1975) concluded that the Troublesome Formation (and equivalent units in northern Colorado and Wyoming) contains abundant eolian, volcanogenic material from various sources.

Driller's logs suggest that individual and locally stacked stream-channel deposits (~1–55 ft thick) are more common near the depositional margins of the Fraser basin. Thick intervals of finer-grained strata (probably mostly siltstone) are more common in the rest of the basin. Siltstone has massive bedding, and locally contains thin (0.8–8 in.) beds and lenses of tuff, some of which has been altered to smectite (montmorillonite) clay (Zielinski, 1982). Eight of the tuffs in the Troublesome basin near Kremmling have $^{40}Ar/^{39}Ar$ sanidine ages that range from 23.5 Ma to 11.0 Ma (latest Oligocene to late Miocene; Izett and Obradovich, 2001).

The highest preserved strata of Troublesome Formation imply that the Troublesome filled the southern part of the Fraser basin to an altitude of at least 9800 ft and filled the southern part of the Granby basin to an altitude of at least 9200 ft (Fig. 8). The narrow canyon (locally as deep as 1000 ft deep between Tabernash and Granby), cut by the modern Fraser River into Proterozoic basement, indicates that the river course was established on the upper surface of the Troublesome and then superimposed during later incision. Downcutting (probably late Miocene or later) led to the Fraser River cutting the canyon and removing much of the Troublesome from the Fraser and Granby

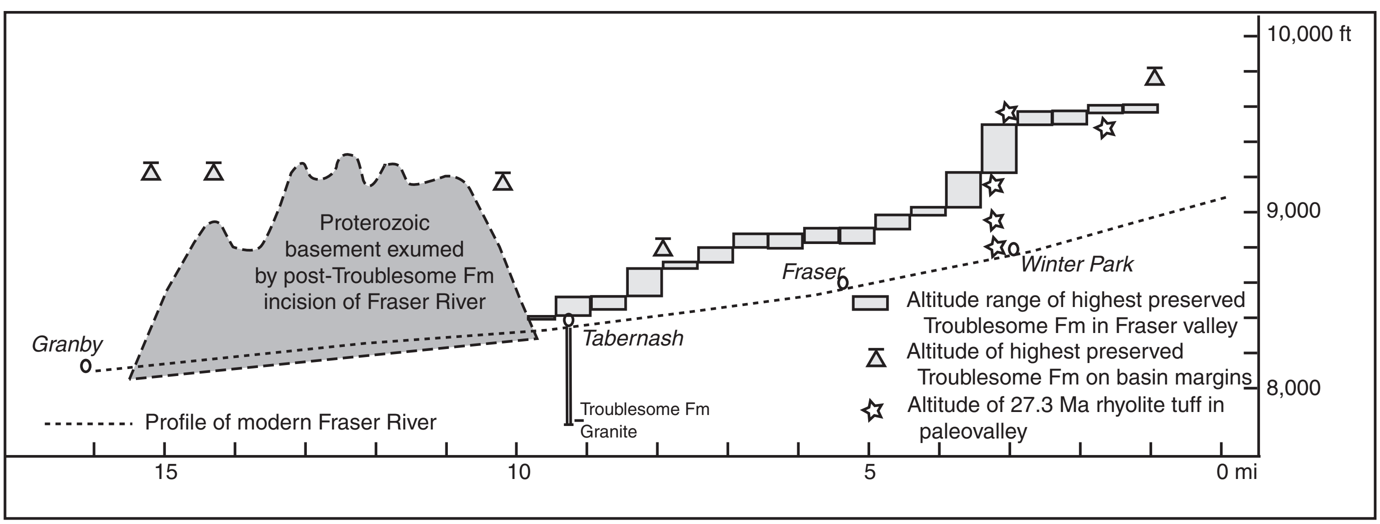

Figure 8. Schematic diagram showing profile of the modern Fraser River; elevations of highest remnants of the Troublesome Formation east of the Fraser River; elevation of base of Troublesome Formation penetrated in a drill hole; and topographic profile of pre-Tertiary bedrock on southwest side of canyon cut by the Fraser River. Distance is along the Fraser River downstream of Jim Creek. Drill hole near Tabernash penetrated 603 ft of Troublesome Formation and 17 ft of Proterozoic basement. Rectangles indicate ranges in elevation of the eroded top of the Troublesome Formation. Several drill holes near Fraser (not shown on figure) penetrated 65–171 ft of Troublesome Formation.

basins during the late Neogene and Quaternary. Fossil vertebrate remains of Hemphillian age (late Miocene and early Pliocene; Robinson, 1972), within fluvial beds deposited in a paleovalley of the Williams Fork cut in the Troublesome Formation, indicate that the courses of Williams Fork, Colorado River, and the Fraser River in the Granby and Fraser basins were established during late Miocene or early Pliocene time.

Depart Fraser valley southward on U.S. 40, traverse Berthoud Pass to Empire, and rejoin I-70 eastbound to Denver.

ACKNOWLEDGMENTS

This field trip guide benefitted from technical reviews by W.R. Keefer and K.J. Turner (USGS). Illustrations were prepared by L.J. Ulibarri and J.C. Cole (USGS), and by I.M. Miller (DMNS).

REFERENCES CITED

Barnhart, C.H., 1941, The Eocene Flora of the Middle Park Formation: Boulder, University of Colorado.

Beekly, A.L., 1915, Geology and coal resources of North Park, Colorado: U.S. Geological Survey Bulletin 596, 121 p.

Blackstone, D.L., Jr., 1975, Late Cretaceous and Cenozoic history of the Laramie Basin region, southeast Wyoming, *in* Curtis, B.F., ed., Cenozoic history of the southern Rocky Mountains: Geological Society of America Memoir 144, p. 249–279.

Braddock, W.A., 1968, Geology of the Empire quadrangle, Grand, Gilpin, and Clear Creek Counties, Colorado: U.S. Geological Survey Professional Paper 616, 56 p., scale 1:24,000.

Braddock, W.A., and Cole, J.C., 1990, Geologic map of Rocky Mountain National Park and vicinity: U.S. Geological Survey Miscellaneous Investigations Series Map I-1973, scale 1:50,000.

Brown, R.W., 1962, Paleocene flora of the Rocky Mountains and Great Plains: U.S. Geological Survey Professional Paper 375, 119 p.

Cobban, W.A., Kennedy, W.J., and Scott, G.R., 1992, Upper Cretaceous Heteromorph Ammonites from the *Baculites compressus* Zone of the Pierre Shale, Colorado: U.S. Geological Survey Bulletin 2024, p. A1–A11, 3 pl.

Cobban, W.A., Walaszczyk, I., Obradovich, J.D., and McKinney, K.C., 2006, A USGS zonal table for the Upper Cretaceous Middle Cenomanian-Maastrichtian of the Western Interior of the United States based on ammonites, inoceramides, and radiometric ages: U.S. Geological Survey Open-File Report 2006-1250.

Cole, J.C., and Braddock, W.A., 2009, Geologic Map of the Estes Park 30′ × 60′ quadrangle, north-central Colorado: U.S. Geological Survey Scientific Investigations Map 2009-3039, scale 1:100,000, 56 p.

Cole, J.C., Larson, E., Farmer, L., and Kellogg, K.S., 2008, The Search for Braddock's Caldera - Guidebook for Colorado Scientific Society Fall 2008 Field Trip, Never Summer Mountains, Colorado: U.S. Geological Survey Open-File Report 2008-1360, 30 p.

Cole, J.C., Braddock, W.A., and Brandt, T.R., 2010, Preliminary geologic map of the Bowen Mountain quadrangle, Grand and Jackson Counties, Colorado: U.S. Geological Survey Open-File Report 2010-3221, 17 p., scale 1:24,000 (in press).

Dickinson, W.R., and Snyder, W.S., 1978, Plate tectonics of the Laramide orogeny, *in* Matthews, V., ed., Laramide folding associated with basement block faulting in the western United States: Geological Society of America Memoir 151, p. 355–366.

Dickinson, W.R., Klute, M.A., Hayes, M.J., Janecke, S.U., Lundin, E.R., McKittrick, M.A., and Olivares, M.D., 1988, Paleogeographic and paleotectonic setting of Laramide sedimentary basins in the central Rocky Mountain region: Geological Society of America Bulletin, v. 100, p. 1023, doi: 10.1130/0016-7606(1988)100<1023:PAPSOL>2.3.CO;2.

Eaton, G.P., 2008, Epeirogeny in the Southern Rocky Mountains region: Evidence and origin: Geosphere, v. 4, no. 5, p. 764–784, doi: 10.1130/GES00149.1.

Erdmann, C.E., 1941, Preliminary report on the geology of the Coalmont district, Jackson County, Colorado: U.S. Geological Survey Open-File Report, 207 p.

Flores, R.M., 1990, Transverse and longitudinal Gilbert-type deltas, Tertiary Coalmont Formation, North Park Basin, Colorado, USA: International Association of Sedimentology Special Publication, v. 19, p, 223–233.

Geissman, J.W., Snee, L.W., Grasskamp, G.W., Carten, R.B., and Geraghty, E.P., 1992, Deformation and age of the Red Mountain intrusive system (Urad-Henderson molybdenum deposits), Colorado—Evidence from paleomagnetic and $^{40}Ar/^{39}Ar$ data: Geological Society of America Bulletin, v. 104, p. 1031–1047, doi: 10.1130/0016-7606(1992)104<1031:DAAOTR>2.3.CO;2.

Gorton, K.A., 1953, Geology of the Cameron Pass area, Grand, Jackson, and Larimer Counties, Colorado, *in* Wyoming Geological Association Guidebook, 8th Annual Field Conference, Laramie Basin, Wyoming and North Park, Colorado, 1953, p. 87–98.

Hail, W.J., Jr., 1965, Geology of northwestern North Park, Colorado: U.S. Geological Survey Bulletin 1188, 133 p.

Hail, W.J., Jr., 1968, Geology of southwestern North Park and vicinity, Colorado: U.S. Geological Survey Bulletin 1257, 119 p.

Hail, W.J., Jr., and Leopold, E.B., 1960, Paleocene and Eocene age of the Coalmont Formation, North Park, Colorado: U.S. Geological Survey Professional Paper 400-B, p, 260–261.

Hayden, F.V., 1869, Preliminary field report [third annual] of the U.S. Geological Survey of Colorado and New Mexico: Washington D.C., U.S. Government Printing Office.

Hendricks, M.L., 1978, Stratigraphy of the Coalmont Formation near Coalmont, Jackson County, Colorado, *in* Hodgson, H.E., ed., Proceedings of the second symposium on the geology of Rocky Mountain coal—1977: Colorado Geological Survey, Resource Series 4, p. 35–47.

Hickey, L.J., 1977, Stratigraphy and paleobotany of the Golden Valley Formation (early Tertiary) of western North Dakota: Geological Society of America Memoir 150, 303 p.

Izett, G.A., 1968, Geology of the Hot Sulphur Springs quadrangle, Grand County, Colorado: U.S. Geological Survey Professional Paper 586, 79 p., scale 1:48,000.

Izett, G.A., 1974, Geologic map of the Trail Mountain quadrangle, Grand County, Colorado: U.S. Geological Survey Geologic Quadrangle Map GQ-1156, scale 1:24,000.

Izett, G.A., 1975, Late Cenozoic sedimentation and deformation in northern Colorado and adjoining areas, *in* Curtis, B.F., ed., Cenozoic history of the southern Rocky Mountains: Geological Society of America Memoir 144, p. 179–210.

Izett, G.A., and Barclay, C.S.V., 1973, Geologic map of the Kremmling quadrangle, Grand County, Colorado: U.S. Geological Survey Geologic Quadrangle Map GQ-1115, scale 1:62,500.

Izett, G.A., and Obradovich, J.D., 2001, $^{40}Ar/^{39}Ar$ ages of Miocene tuffs in basin-fill deposits (Santa Fe Group, New Mexico, and Troublesome Formation, Colorado) of the Rio Grande rift system: The Mountain Geologist, v. 38, p. 77–86.

Izett, G.A., Taylor, R.B., and Hoover, D.L., 1963, Windy Gap Volcanic Member of the Middle Park Formation, Middle Park, Colorado: U.S. Geological Survey Professional Paper 450-E, p, E36–E39.

Izett, G.A., Cobban, W.A., and Gill, J.R., 1971, The Pierre Shale near Kremmling, Colorado, and its correlation to the east and west: U.S. Geological Survey Professional Paper, v. 684-A, p. A1–A19.

Johnson, K.R., 1999, Night of the Giant Ammonites: Dinosaur Sites: Natural History Magazine, August issue, p. 14–18.

Johnson, K.R., and Troll, R., 2007, Cruisin' the Fossil Freeway: An epoch tale of a scientist and an artist on the ultimate 5,000 mile paleo road trip: Golden, Colorado, Fulcrum Press, 204 p.

Kauffman, E.G., Upchurch, G.R., Jr., and Nichols, D.J., 1990, The Cretaceous-Tertiary interval at South Table Mountain, near Golden, Colorado, *in* Kauffman, E.G., and Walliser, O.H., eds., Extinction events in Earth history: Lecture notes in Earth sciences: New York, Springer-Verlag, v. 30, p. 365–392.

Kinney, D.M., 1970, Preliminary geologic map of the Rand quadrangle, North Park, Jackson County, Colorado: U.S. Geological Survey Open-File Report 70-183, scale 1:48,000.

Knox, K.L., 2005, The Never Summer igneous complex: Evolution of a shallow magmatic system [master's thesis]: Boulder, Colorado, University of Colorado, 54 p.

Madden, D.H., 1977, Exploratory drilling in the Coalmont coal field, Jackson County, Colorado, June–November, 1977: U.S. Geological Survey Open-File Report 77-887, 15 p.

Madole, R.F., 1991a, Surficial geologic map of the Walden 30′ × 60′ quadrangle, Jackson, Larimer, and Routt Counties, Colorado: U.S. Geological Survey Miscellaneous Investigations map I-1824, scale 1:100,000.

Madole, R.F., 1991b, Surficial geologic map of the Steamboat Springs 30′ × 60′ quadrangle, Grand, Jackson, and Routt Counties, Colorado: U.S. Geological Survey Miscellaneous Investigations map I-1825, scale 1:100,000.
Mark, A., 1958, Geology of the Illinois River–Buffalo Creek area, North Park [M.S. thesis]: Golden, Colorado School of Mines, 72 p.
Marvin, R.F., Young, E.J., Mehnert, H.H., and Naeser, C.W., 1974, Summary of radiometric age determinations on Mesozoic and Cenozoic igneous rocks and uranium and base metal deposits in Colorado: Isochron West, no. 11, 41 p.
McIver, E.E., and Basinger, J.F., 1993, Fossil flora of the Ravenscrag Formation (Paleocene), southwestern Saskatchewan, Canada: Palaeontographica Canadiana, v. 10, p. 167.
Mears, B., Jr., 1993, Geomorphic history of Wyoming and high-level erosion surfaces, *in* Snoke, A.W., et al., eds., Geology of Wyoming: Geological Survey of Wyoming Memoir No. 5, p. 608–626.
Miller, I.M., Johnson, K.R., and Ellis, B., 2006, An exceptionally preserved Paleocene flora from the Middle Park Formation, Colorado: Implications for the Laramide paleotopography of the Central Rocky Mountain Region [abs.]: Geological Society of America Abstracts with Programs, v. 38, no. 7, p. 380.
de la Montagne, J., 1957, Cenozoic structural and geomorphic history of northern North Park and Saratoga Valley, Colorado and Wyoming, *in* Guidebook to the Geology of North and Middle Parks Basin, Colorado: Rocky Mountain Association of Geologists, p. 36–42.
de la Montagne, J., and Barnes, W.C., 1957, Stratigraphy of the North Park Formation in the North Park area, Colorado, *in* Guidebook to the Geology of North and Middle Parks Basin, Colorado: Rocky Mountain Association of Geologists, p. 55–60.
Newberry, J.S., 1868, Notes on the later extinct floras of North America, with descriptions of some new species of fossil plants from the Cretaceous and Tertiary strata: Lyceum Natural History New York Annals, v. 9, p. 1–76.
Nichols, D.J., 2003, Palynostratigraphic framework for age determination and correlation of the nonmarine lower Cenozoic of the Rocky Mountains and Great Plains region, *in* Raynolds, R.G., and Flores, R.M., eds., Cenozoic Systems of the Rocky Mountain Region: Denver, Rocky Mountain SEPM, p. 107–134.
Nichols, D.J., 2009, On the palynomorph-based biozones in Paleogene strata of the Rocky Mountain basis: The Mountain Geologist, v. 46, p. 105–124.
Obradovich, J.D., 2002, Geochronology of Laramide synorogenic strata in the Denver Basin, Colorado: Rocky Mountain Geology, v. 37, no. 2, p, 165–171.
Obradovich, J.D., and Cobban, W.A., 1975, A time-scale for the Late Cretaceous of the western interior of North America, *in* Caldwell, W.G.E., ed., The Cretaceous System in the Western Interior of North America: Montreal, Quebec, Geological Association of Canada Special Paper 13, Les Presses Elites, p. 31–54.
O'Neill, J.M., 1981, Geologic map of the Mount Richthofen quadrangle and the western part of the Fall River Pass quadrangle, Grand and Jackson Counties, Colorado: U.S. Geological Survey Miscellaneous Investigations Map I-1291, scale 1:24,000.
Raynolds, R.G., 2002, Upper Cretaceous and Tertiary stratigraphy of the Denver Basin, Colorado: Rocky Mountain Geology, v. 37, p. 111–134.
Raynolds, R.G., and Johnson, K.R., Ellis, B., Dechesne, M., and Miller, I.M., 2007, Earth history along Colorado's Front Range: Salvaging geologic data in the suburbs and sharing it with the citizens: GSA Today, v. 17, no. 12, p. 4–10.
Roberts, S.B., and Rossi, G.S., 1999, A summary of coal in the Coalmont Formation (Tertiary), North Park Basin, Colorado, Chapter SN, *in* U.S. Geological Survey, ed., 1999 Resource assessment of selected Tertiary coal beds and zones in the northern Rocky Mountains and Great Plains region: U.S. Geological Survey Professional Paper 1625-A, p. SN-1–15.
Robinson, P., 1972, Tertiary history, *in* Mallory, W.W., ed., Geologic atlas of the Rocky Mountain region: Denver, Hirschfeld Press, Rocky Mountain Association of Geologists, p. 233–242.
Schroeder, D.A., 1995, Geologic map of the Granby quadrangle, Grand County, Colorado: U.S. Geological Survey Geologic Quadrangle Map GQ-1763, scale 1:24,000.
Scott, G.R., 1972, Geologic map of the Morrison quadrangle, Jefferson County, Colorado: U.S. Geological Survey Miscellaneous Investigations Map I-790-A, scale 1:24,000.
Shroba, R.R., Bryant, B., Kellogg, K.S., Theobald, P.K., and Brandt, T.R., 2010, Geologic map of the Fraser 7.5-minute quadrangle, Grand County, Colorado: U.S. Geological Survey Scientific Investigations Map 3130, scale 1:24,000 (in press).
Snyder, G.L., 1980, Geologic map of the northernmost Park Range and southernmost Sierra Madre, Jackson and Routt Counties, Colorado: U.S. Geological Survey Miscellaneous Investigations Map I-1113, scale 1:48,000.
Soister, P.E., 1978, Stratigraphy of uppermost Cretaceous and lower Tertiary rocks of the Denver Basin, *in* Pruitt, J.D., and Coffin, P.E., eds., Energy resources of the Denver Basin: Denver, Colorado, Rocky Mountain Association of Geologists Symposium, p. 223–230.
Stands, R.E., 1992, Relative ages of major coal beds in the Coalmont Formation (Paleocene-Eocene), North Park Basin, Jackson County, Colorado [M.S. thesis]: Golden, Colorado, Colorado School of Mines, 91 p.
Stearns, D.W., 1978, Faulting and forced folding in the Rocky Mountains foreland, *in* Matthews, V., III, ed., Laramide folding associated with basement block faulting in the western United States: Geological Society of America Memoir 151, p. 1–38.
Stein, H.J., and Crock, J.G., 1990, Late Cretaceous-Tertiary magmatism in the Colorado Mineral Belt–Rare earth element and samarium-neodymium isotopic studies, *in* Anderson, J.L., ed., The nature and origin of Cordilleran magmatism: Geological Society of America Memoir 174, p. 195–223.
Steven, T.A., 1956, Cenozoic geomorphic history of the Medicine Bow Mountains near the Northgate fluorspar district, Colorado: Colorado Scientific Society: Proceedings, v. 17, no. 2, p. 35–55.
Steven, T.A., 1960, Geology and fluorspar deposits, Northgate District, Colorado: U.S. Geological Survey Bulletin 1082-F, p. 323–422, map scale 1:24,000.
Steven, T.A., Evanoff, E., and Yuhas, R.H., 1997, Middle and Late Cenozoic tectonic and geomorphic development of the Front Range, Colorado, *in* Bolyard, D.W., and Sonnenberg, S.A., eds., Geologic history of the Colorado Front Range: Rocky Mountain Association of Geologists, p. 115–124.
Taylor, R.B., 1975, Geologic map of the Bottle Pass quadrangle, Grand County, Colorado: U.S. Geological Survey Geologic Quadrangle Map GQ-1224, scale 1:24,000.
Tweto, O., 1957, Geologic sketch of southern Middle Park, Colorado, *in* Guidebook to the Geology of North and Middle Parks Basin, Colorado: Rocky Mountain Association of Geologists, p. 18–31.
Tweto, O., 1975, Laramide (Late Cretaceous–early Tertiary) orogeny in the Southern Rocky Mountains, *in* Curtis, B.F., ed., Cenozoic history of the southern Rocky Mountains: Geological Society of America Memoir 144, p. 1–44.
Tweto, O., 1976, Geologic map of the Craig 1° × 2° quadrangle, Colorado: U.S. Geological Survey Miscellaneous Investigations Map I-972, scale 1:250,000.
Tweto, O. (compiler), 1979, Geologic map of Colorado: U.S. Geological Survey, scale 1:500,000.
Ward, D.E., 1957, Geology of the Middle Fork of the Michigan River, Jackson County, Colorado, *in* Guidebook to the Geology of North and Middle Parks Basin, Colorado: Rocky Mountain Association of Geologists, p. 70–74.
Wellborn, R.E., 1977, Structural style in relation to oil and gas exploration in North Park–Middle Park basin, Colorado, *in* Veal, H.K., ed., Exploration frontiers of the central and southern Rockies: Rocky Mountain Association of Geologists Symposium, p. 41–60.
Wilson, D.W., 2002, Petrographic provenance analysis of Kiowa Core sandstone samples, Denver Basin, Colorado: Rocky Mountain Geology, v. 37, p. 173–187.
Zielinski, R.A., 1982, The mobility of uranium and other elements during alteration of rhyolite ash to montmorillonite—A case study in the Troublesome Formation, Colorado, U.S.A: Chemical Geology, v. 35, p. 185–204, doi: 10.1016/0009-2541(82)90001-8.

Manuscript Accepted by the Society 12 July 2010

Printed in the USA